



US010147473B2

(12) **United States Patent**  
**Yoda et al.**

(10) **Patent No.:** **US 10,147,473 B2**  
(45) **Date of Patent:** **Dec. 4, 2018**

(54) **MAGNETIC MEMORY**

FOREIGN PATENT DOCUMENTS

(71) Applicant: **KABUSHIKI KAISHA TOSHIBA**,  
Minato-ku (JP)

JP 2014-45196 3/2014  
JP 2015-534272 11/2015  
WO WO 2016/190879 A1 12/2016

(72) Inventors: **Hiroaki Yoda**, Kawasaki (JP); **Naoharu Shimomura**, Meguro (JP); **Yoshiaki Saito**, Kawasaki (JP); **Yuichi Ohsawa**, Yokohama (JP); **Keiko Abe**, Yokohama (JP)

OTHER PUBLICATIONS

H. Yoda, et al. "The Progresses of MRAM as a Memory to Save Energy Consumption and Its Potential for Further Reduction", Symposium on VLSI Technology Digest of Technical Papers, 2015, 2 pages.

H. Yoda, et al. "Progress of STT-MRAM Technology and the Effect on Normally-off Computing Systems", IEDM Tech. Dig., 2012, 4 pages.

(73) Assignee: **KABUSHIKI KAISHA TOSHIBA**,  
Minato-ku (JP)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(Continued)

(21) Appl. No.: **15/703,548**

*Primary Examiner* — Tan T. Nguyen

(22) Filed: **Sep. 13, 2017**

(74) *Attorney, Agent, or Firm* — Oblon, McClelland, Maier & Neustadt, L.L.P.

(65) **Prior Publication Data**

US 2018/0174635 A1 Jun. 21, 2018

(30) **Foreign Application Priority Data**

Dec. 16, 2016 (JP) ..... 2016-244769

(57) **ABSTRACT**

(51) **Int. Cl.**  
**G11C 11/16** (2006.01)

A magnetic memory includes: first to third terminals; a conductive layer including first to fifth regions, the first region being electrically connected to the first terminal, the fifth region being electrically connected to the second terminal, and the third region being electrically connected to the third terminal; a first magnetoresistive element including a first magnetic layer, a second magnetic layer disposed between the second region and the first magnetic layer, and a first nonmagnetic layer disposed between the first and the second magnetic layer; a second magnetoresistive element including a third magnetic layer, a fourth magnetic layer disposed between the fourth region and the third magnetic layer, and a second nonmagnetic layer disposed between the third and the fourth magnetic layer; and a circuit flowing a write current between the first and the second terminal and between the second and the third terminal in a write operation.

(52) **U.S. Cl.**  
CPC ..... **G11C 11/1675** (2013.01); **G11C 11/161** (2013.01); **G11C 11/16** (2013.01)

(58) **Field of Classification Search**  
CPC .... G11C 11/1675; G11C 11/161; G11C 11/16  
(Continued)

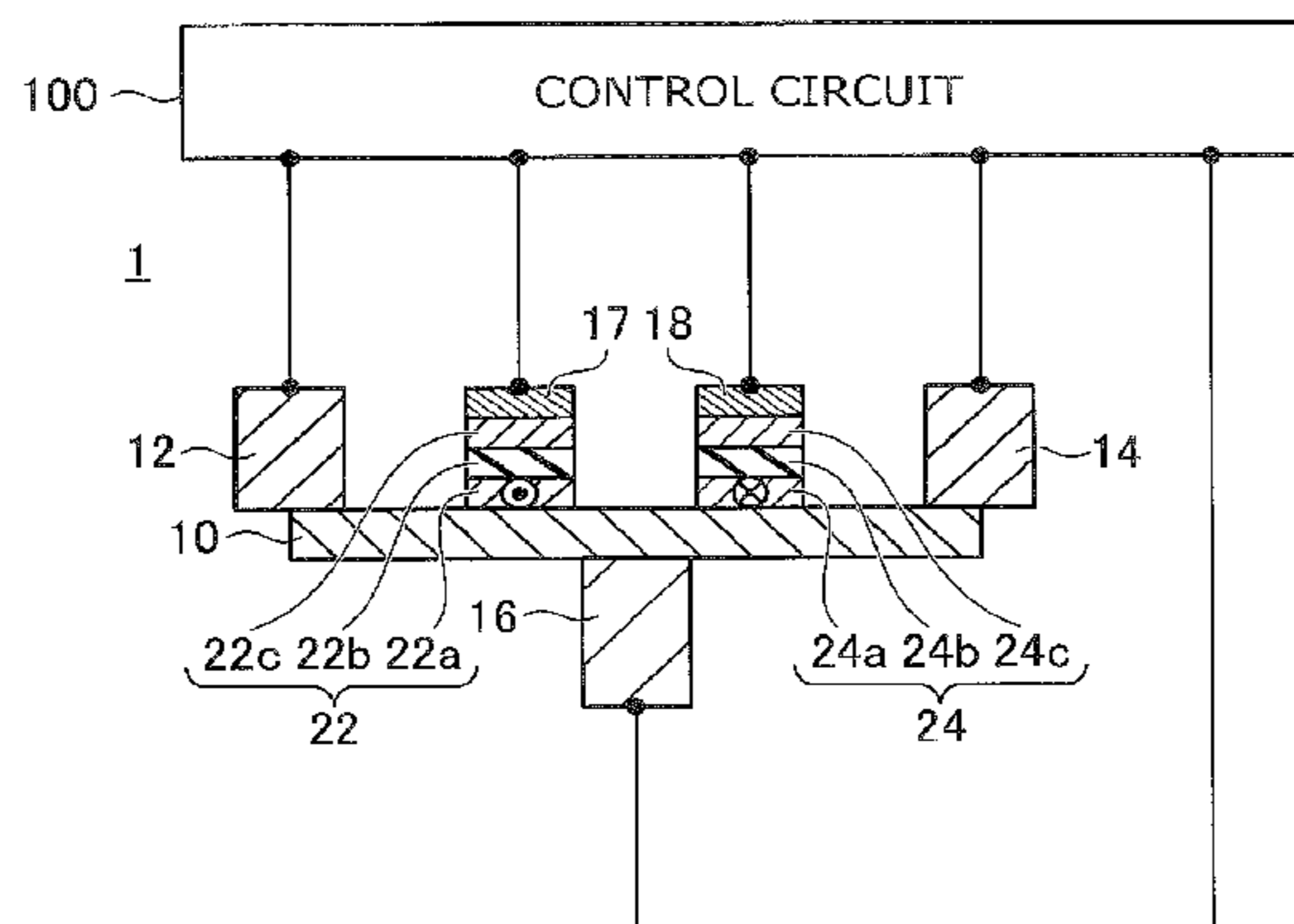
(56) **References Cited**

U.S. PATENT DOCUMENTS

8,837,208 B2 \* 9/2014 Li ..... H01L 43/12  
365/158

9,076,537 B2 7/2015 Khvalkovskiy et al.  
(Continued)

**22 Claims, 48 Drawing Sheets**



(58) **Field of Classification Search**

USPC ..... 365/158, 63, 66, 148, 163, 171, 173  
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

9,412,448	B2	8/2016	Di Pendina et al.	
9,881,660	B2 *	1/2018	Yoda .....	G11C 11/1675
2006/0215445	A1 *	9/2006	Baek .....	H01L 27/2472
				365/158
2015/0236071	A1	8/2015	Lee et al.	
2016/0142012	A1	5/2016	Wang et al.	
2016/0232958	A1	8/2016	Bandiera	
2017/0169872	A1	6/2017	Yoda et al.	
2018/0040807	A1 *	2/2018	Saito .....	H01L 27/228

\* cited by examiner

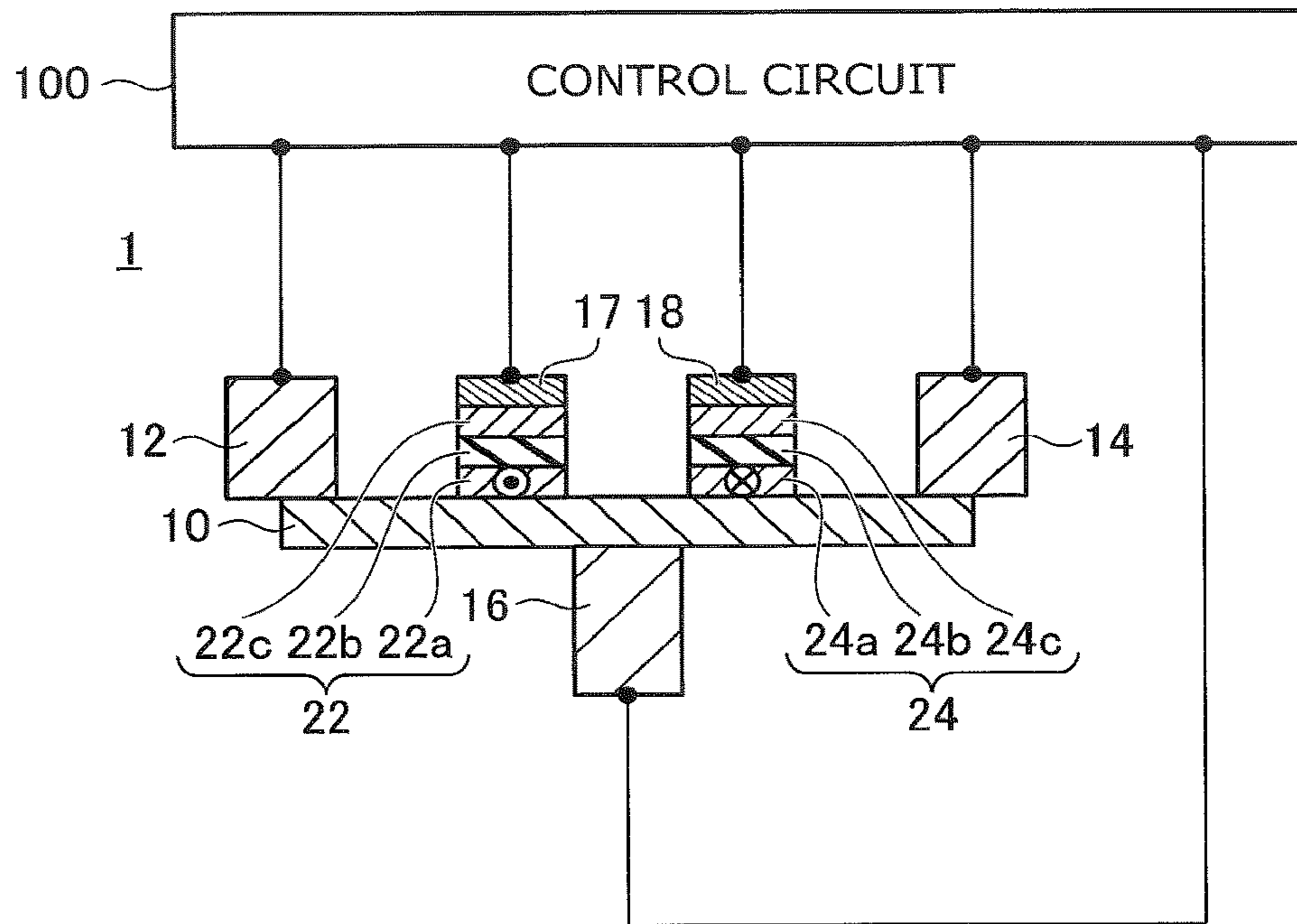


FIG. 1

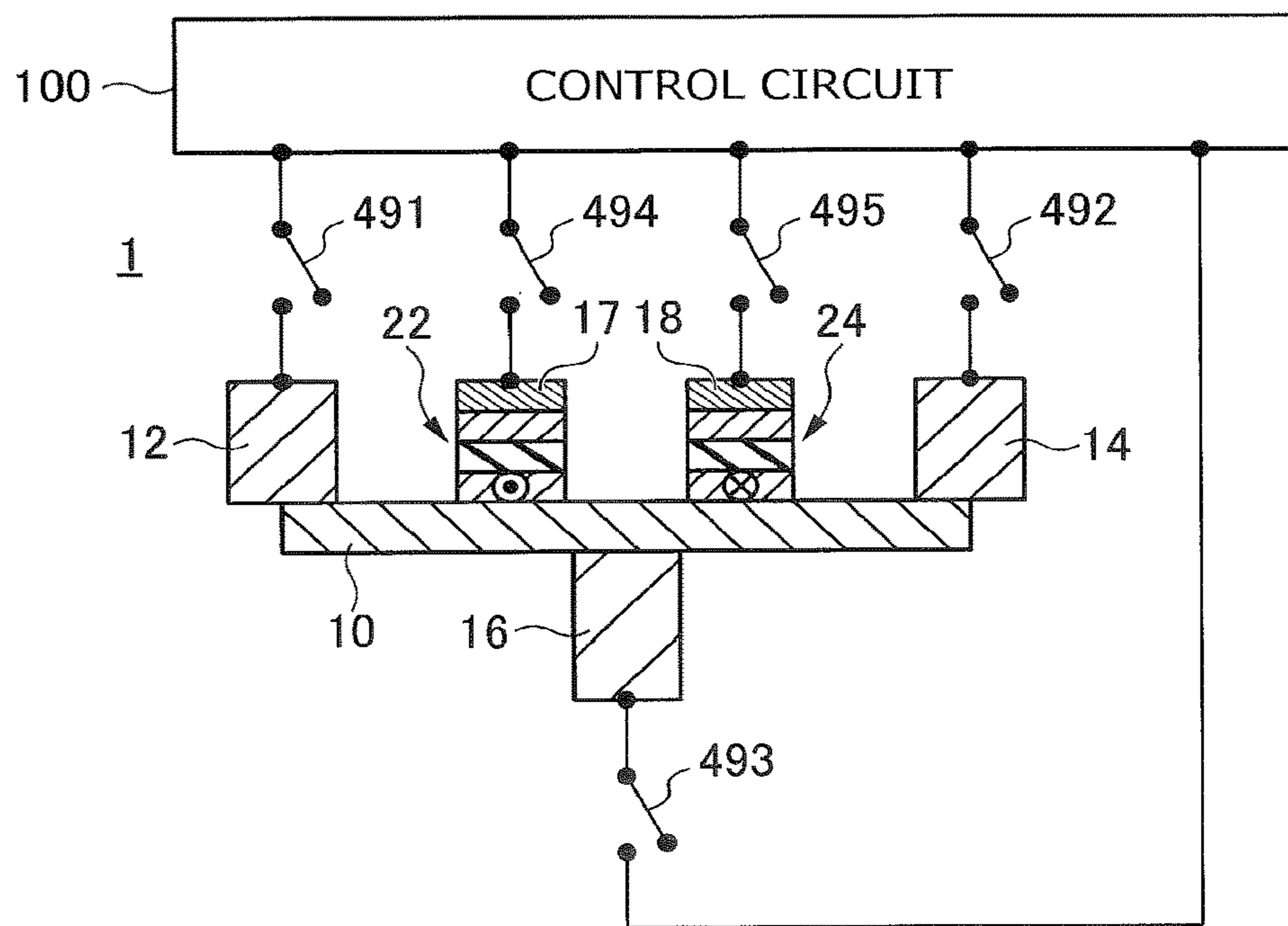


FIG. 2

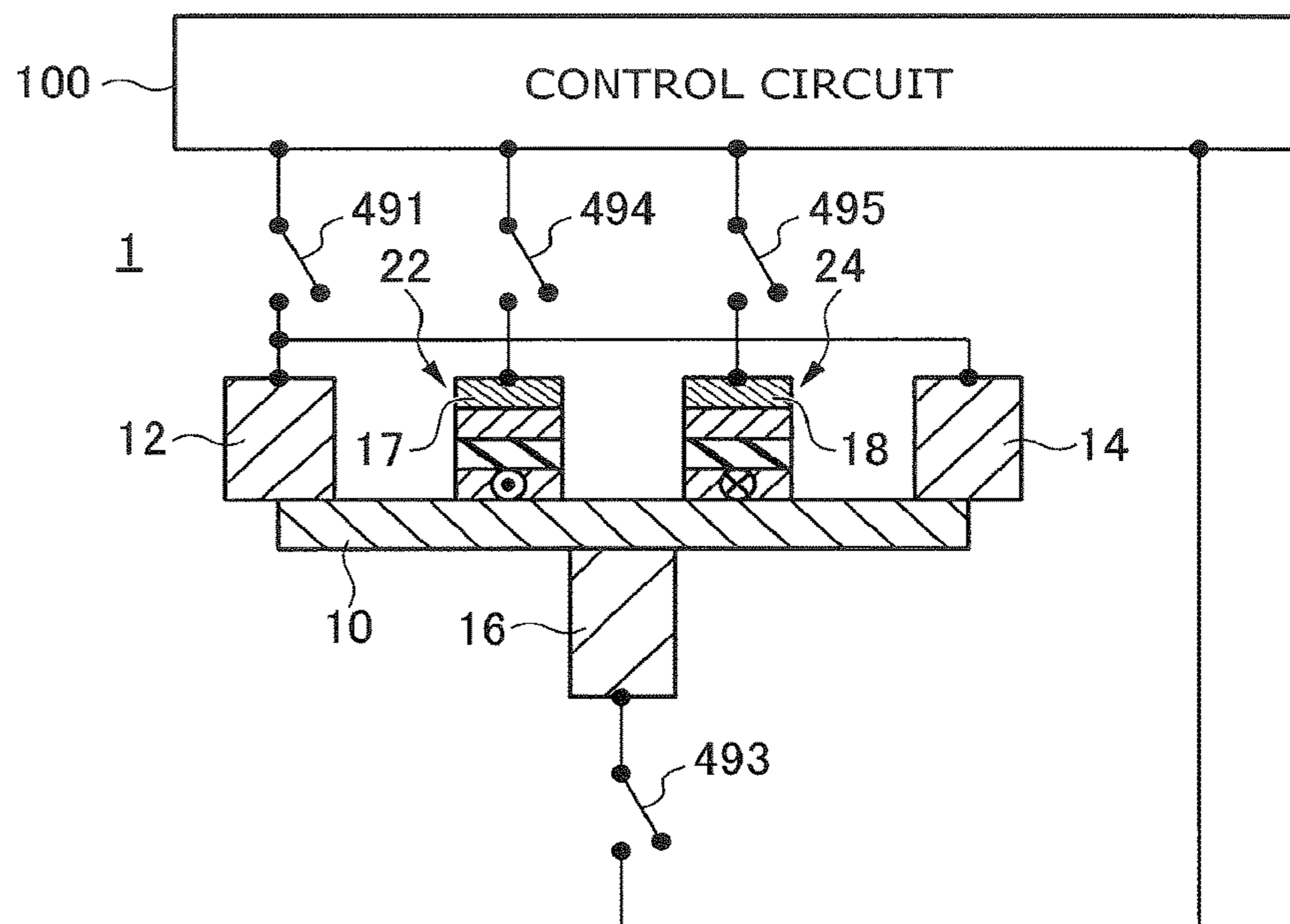


FIG. 3

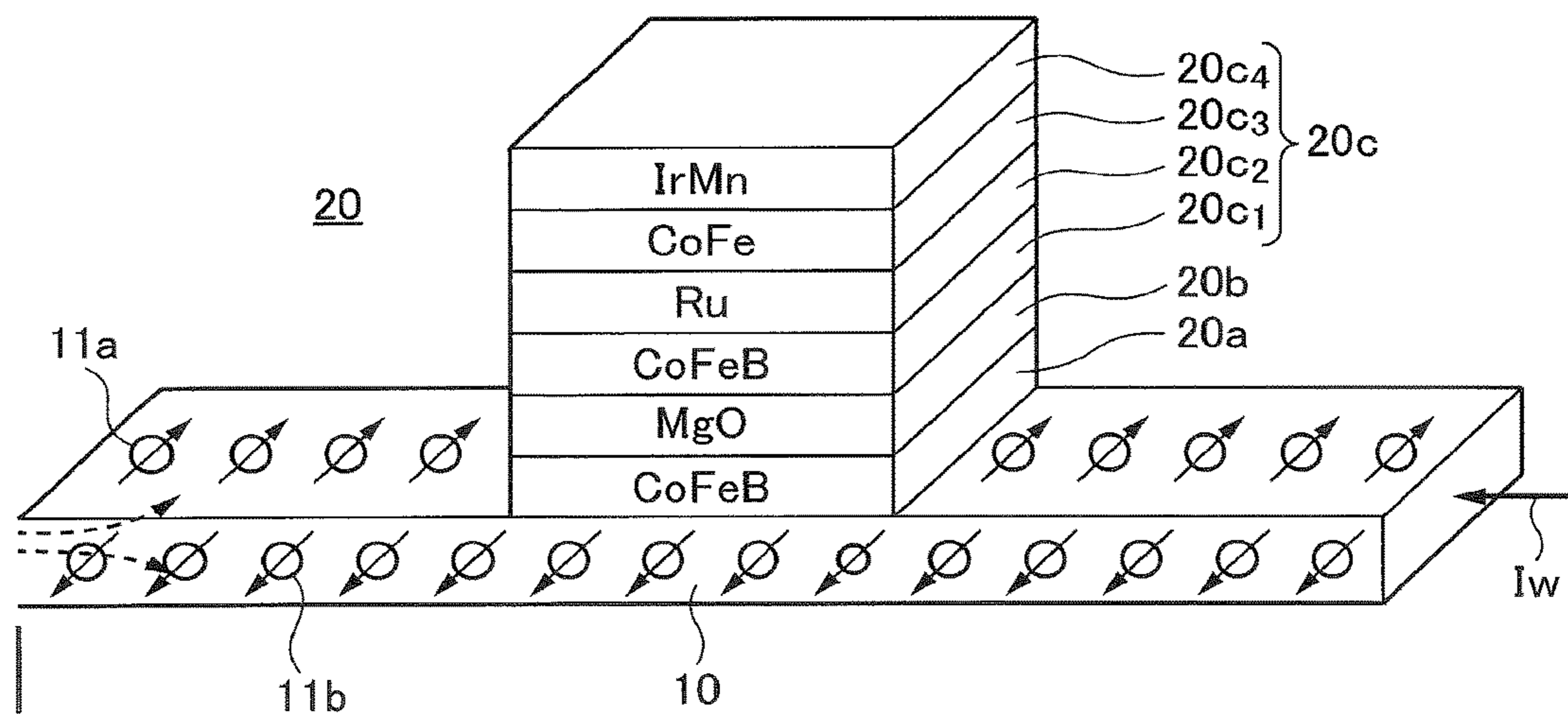


FIG. 4

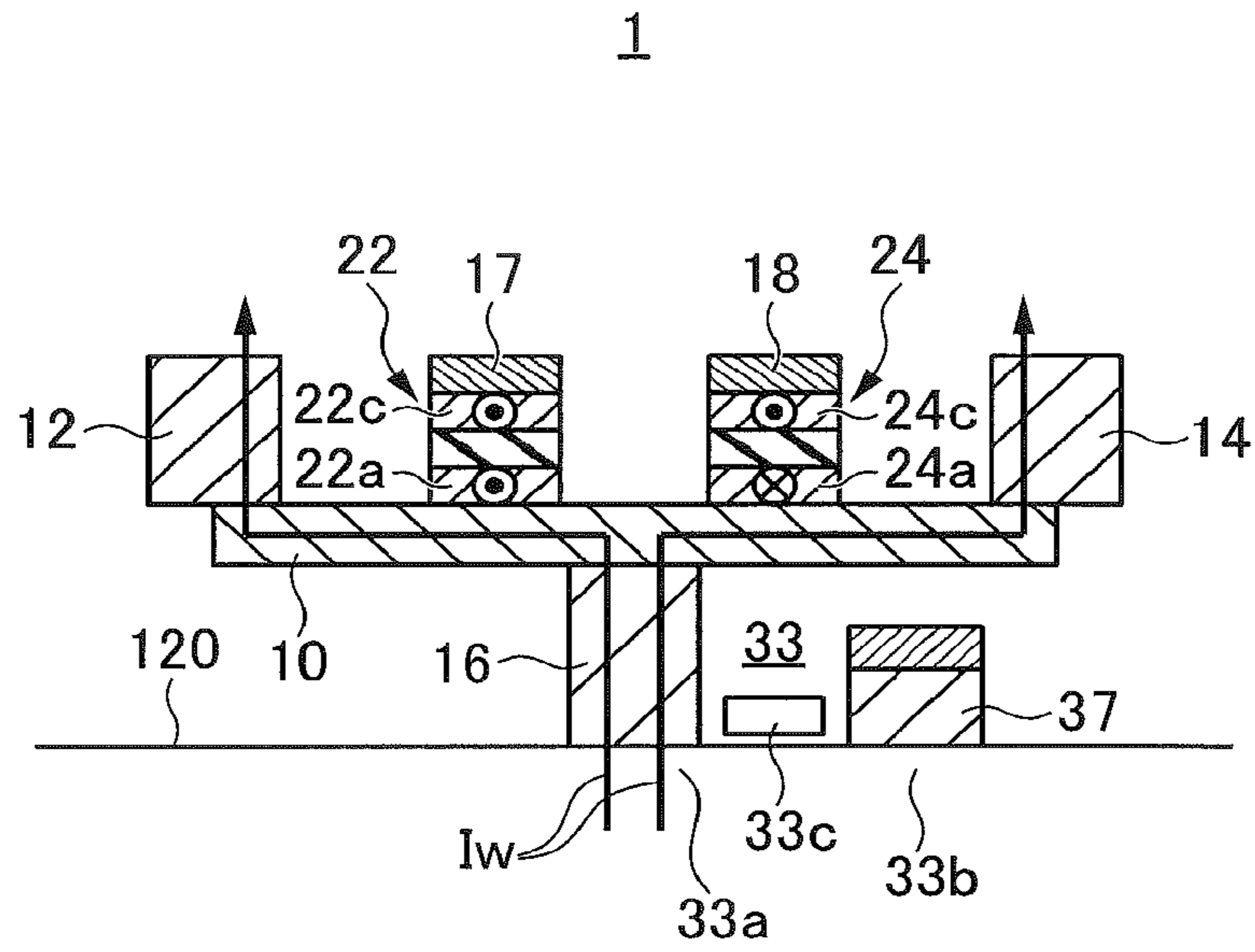


FIG. 5

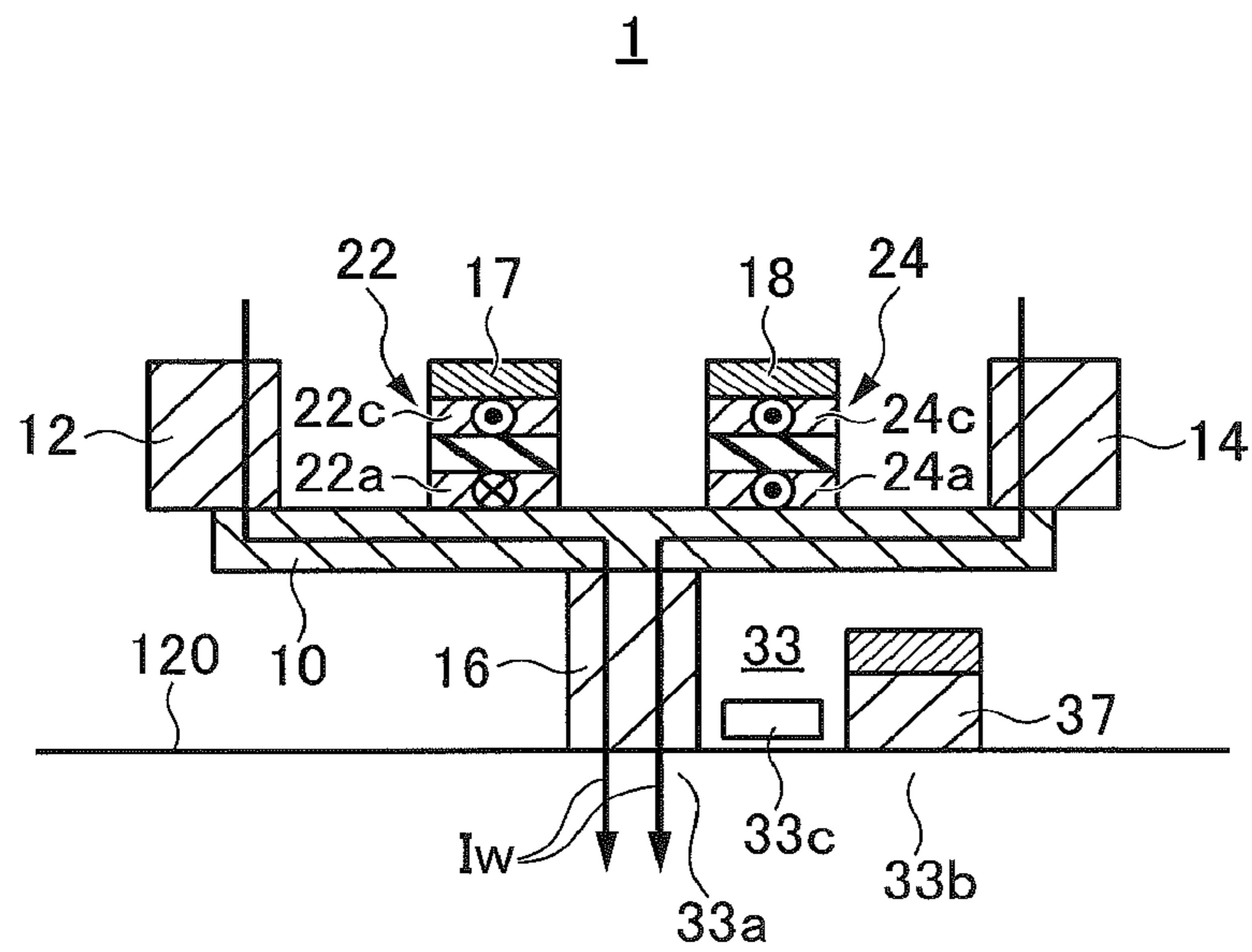


FIG. 6

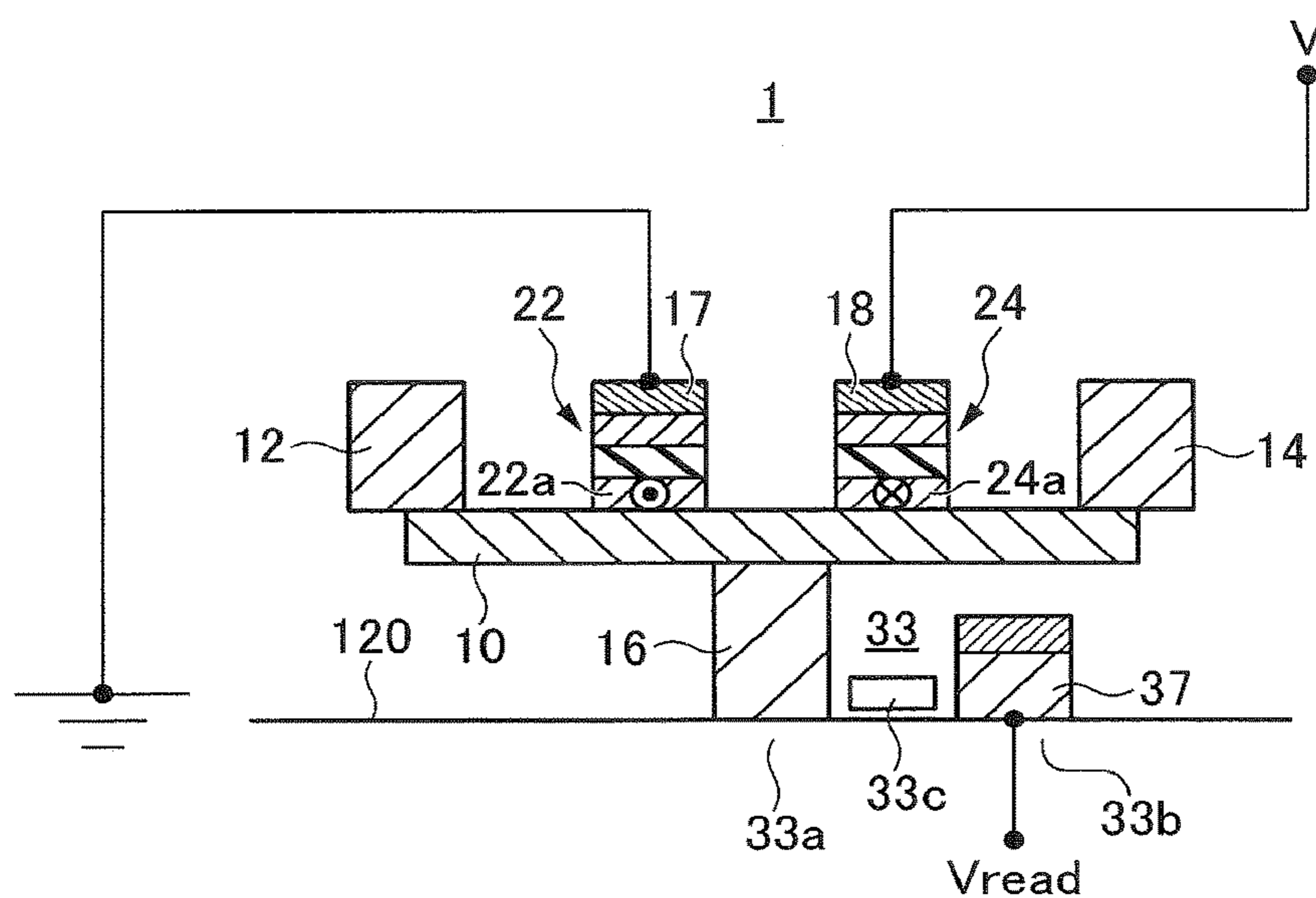


FIG. 7

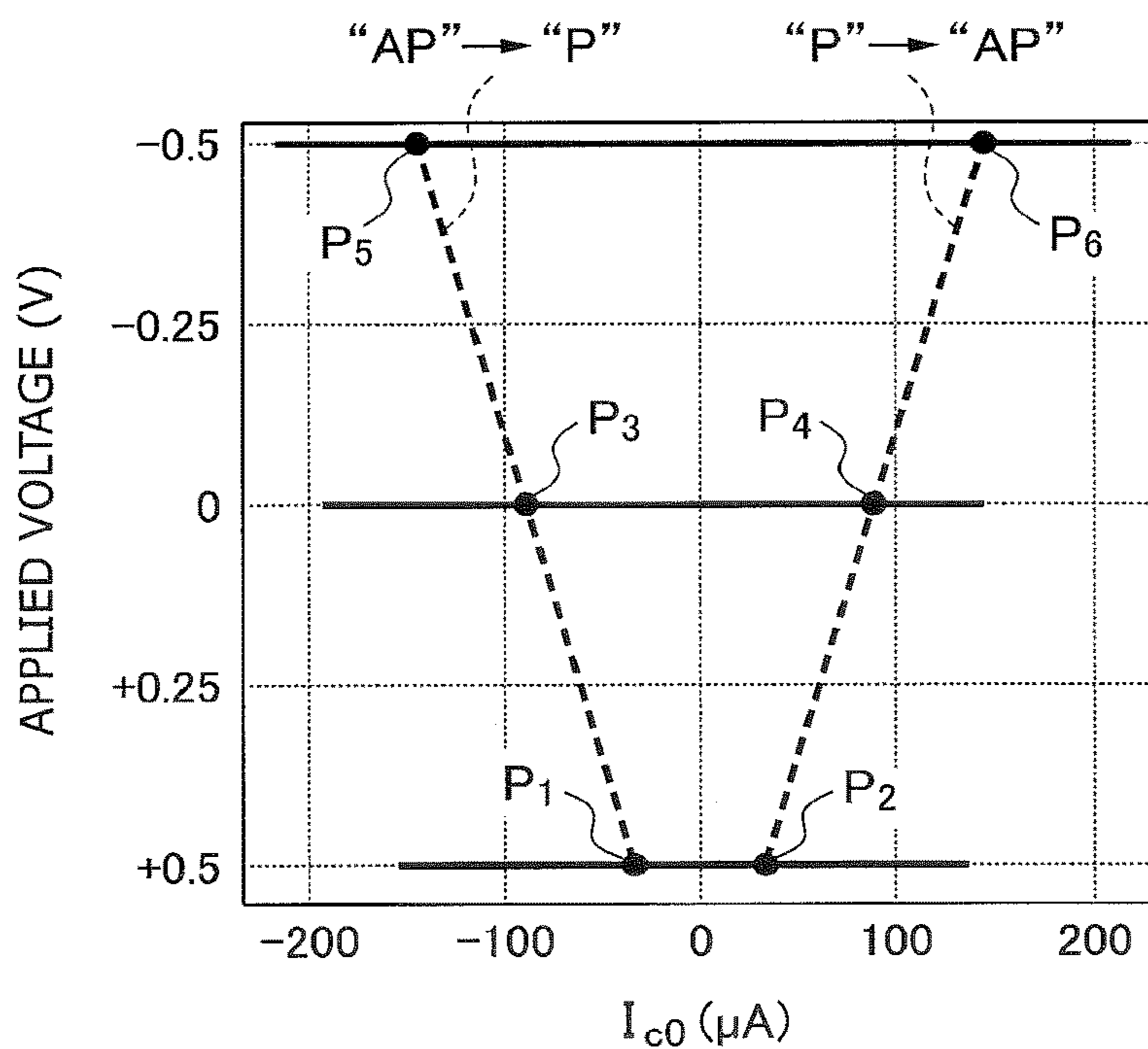


FIG. 8

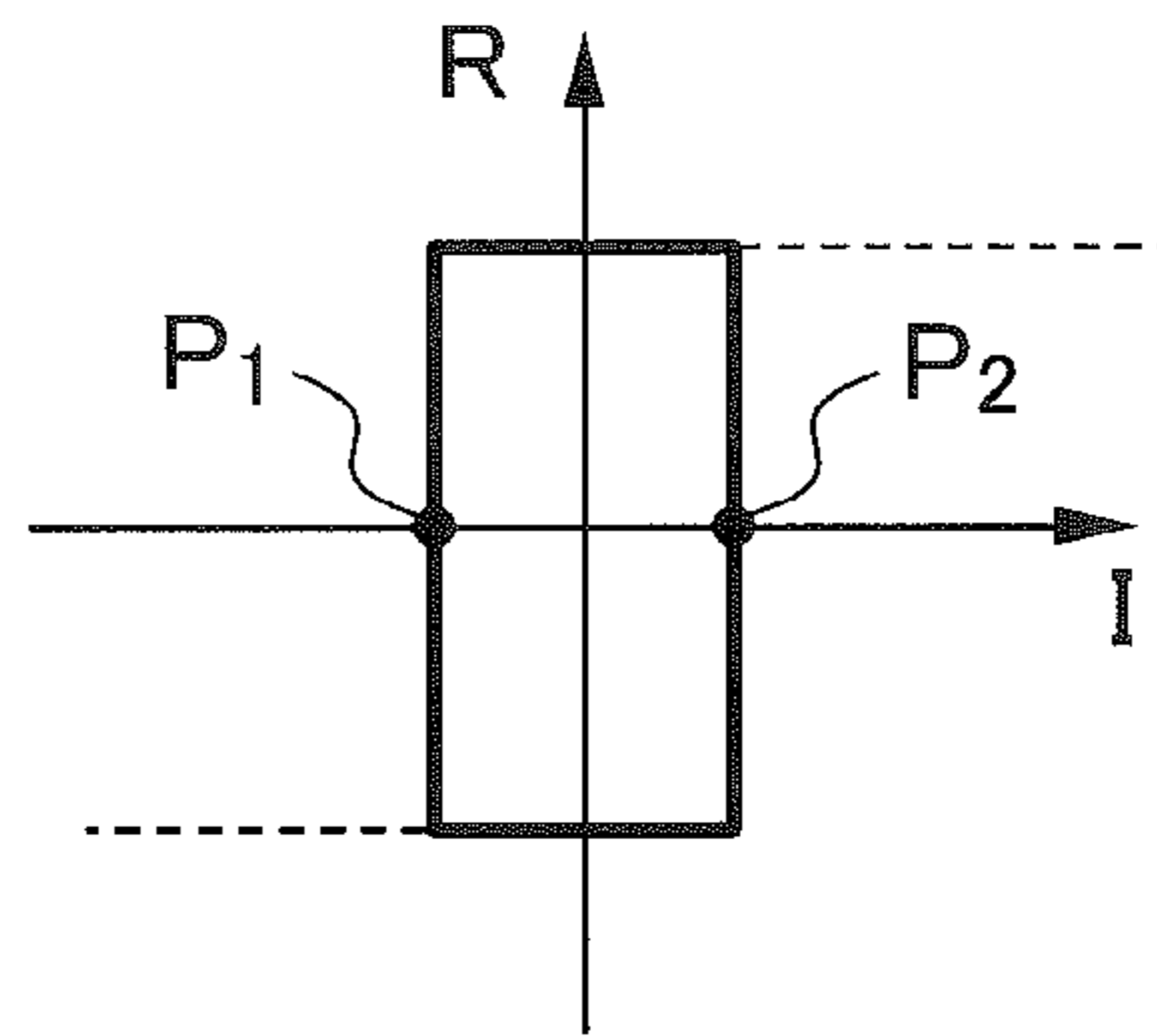


FIG. 9A

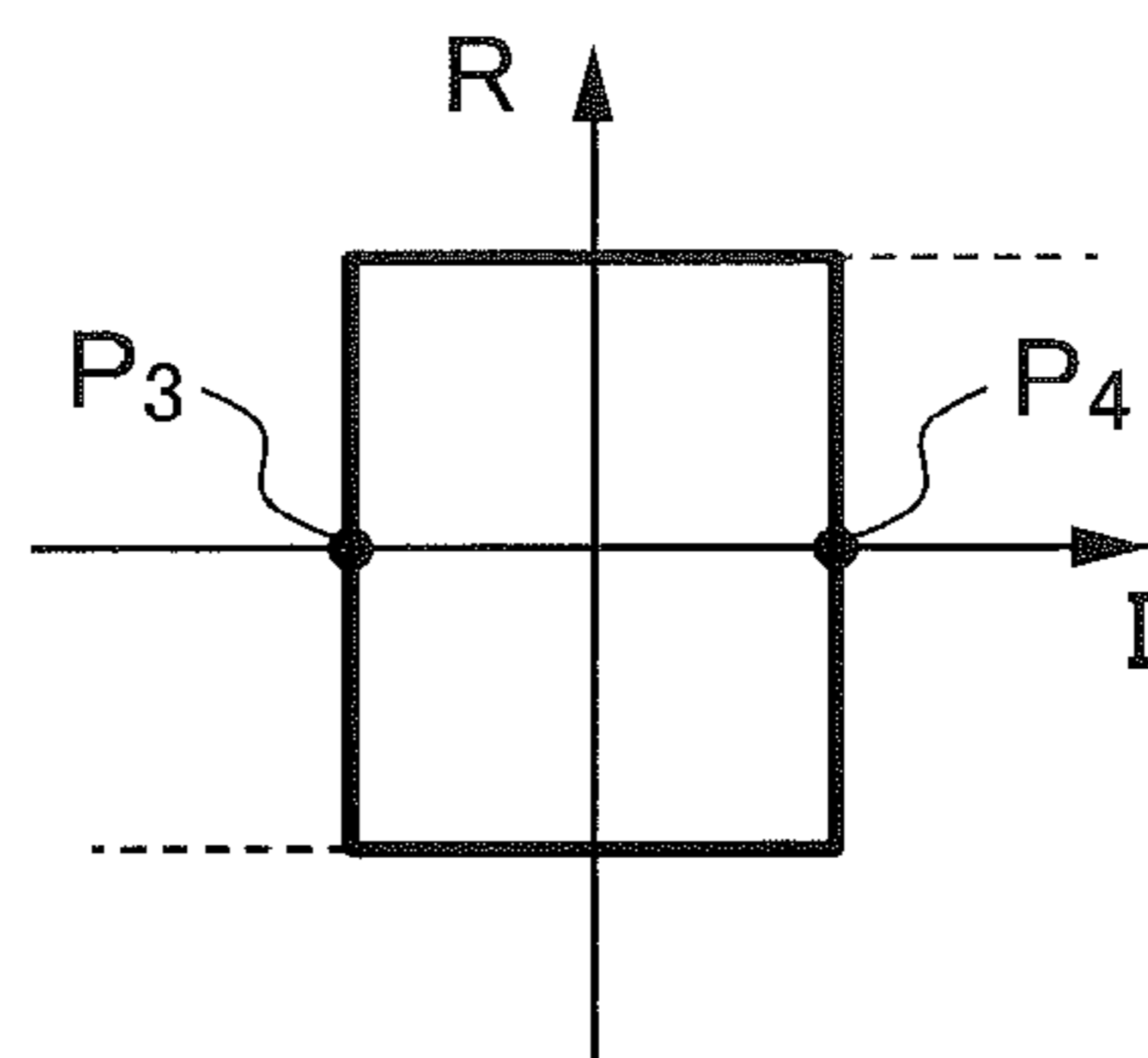


FIG. 9B

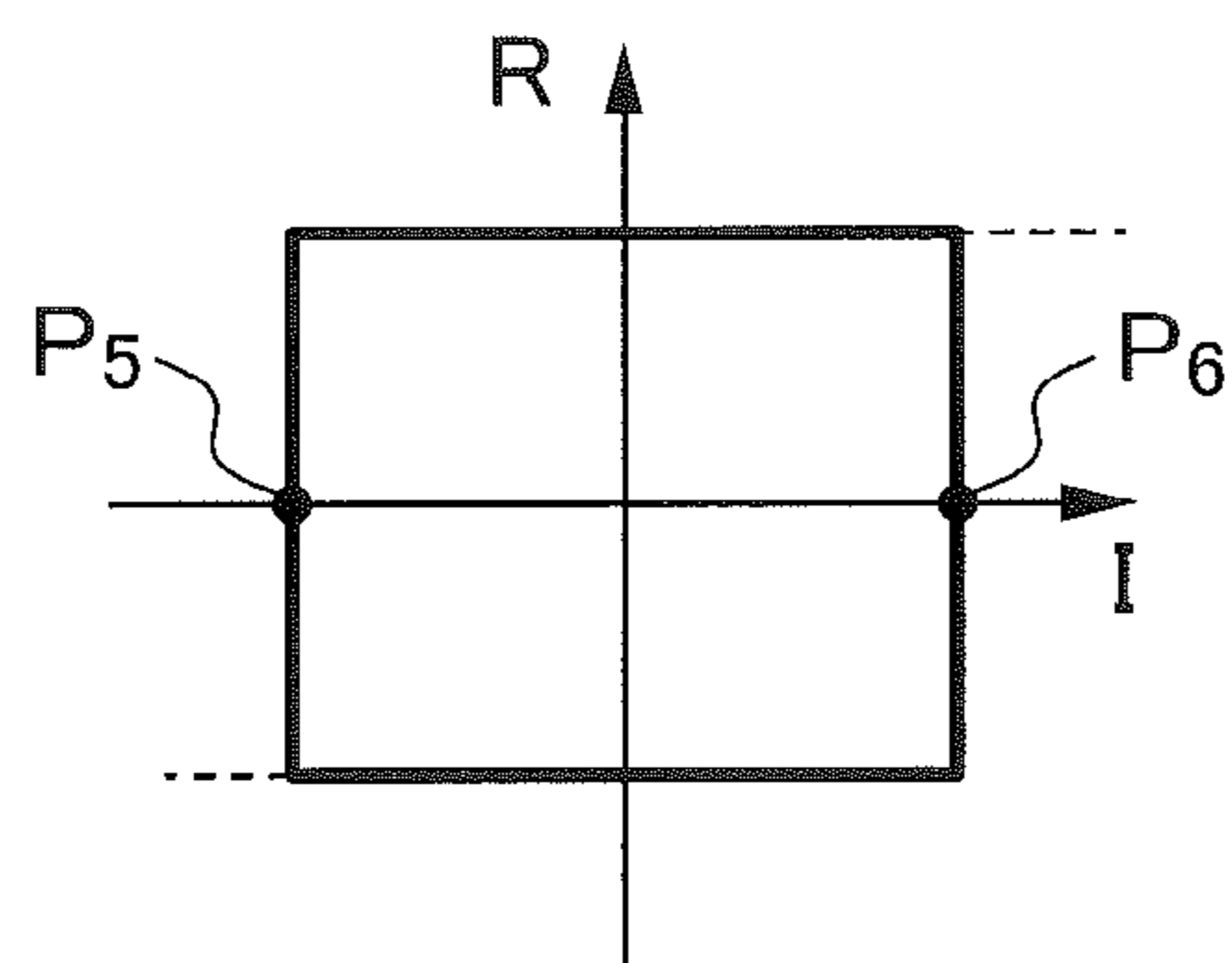


FIG. 9C

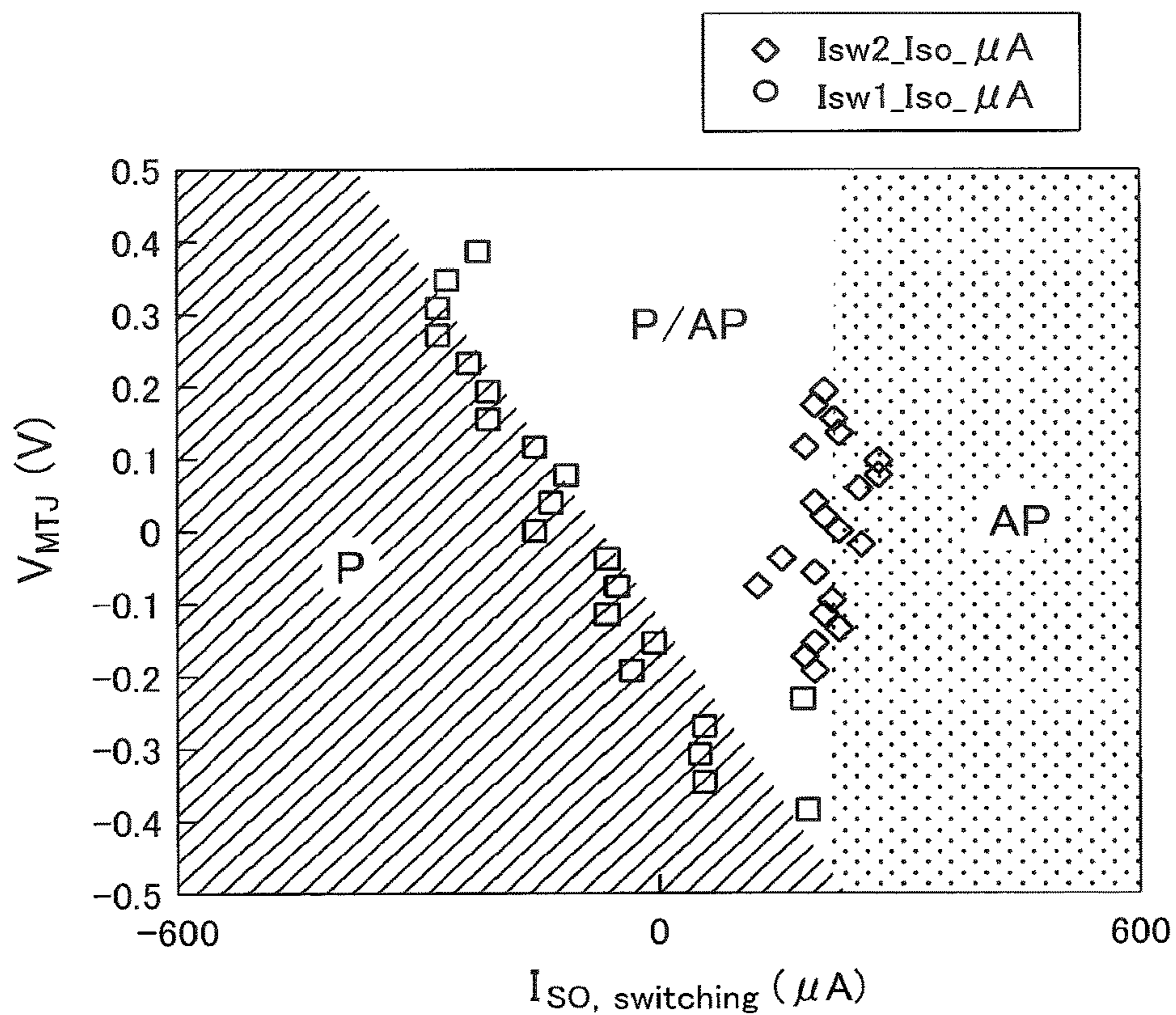


FIG. 10

1

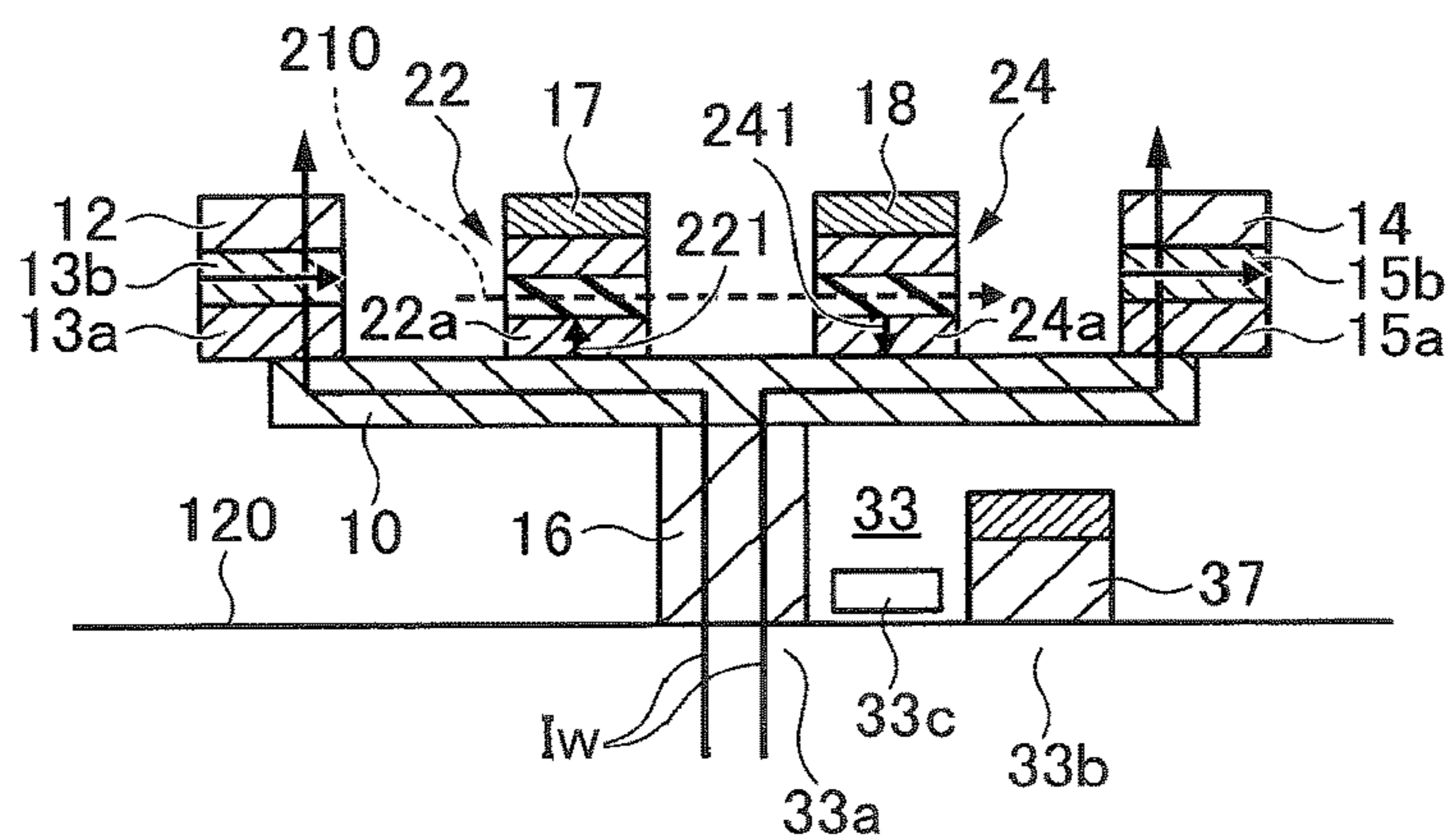


FIG. 11



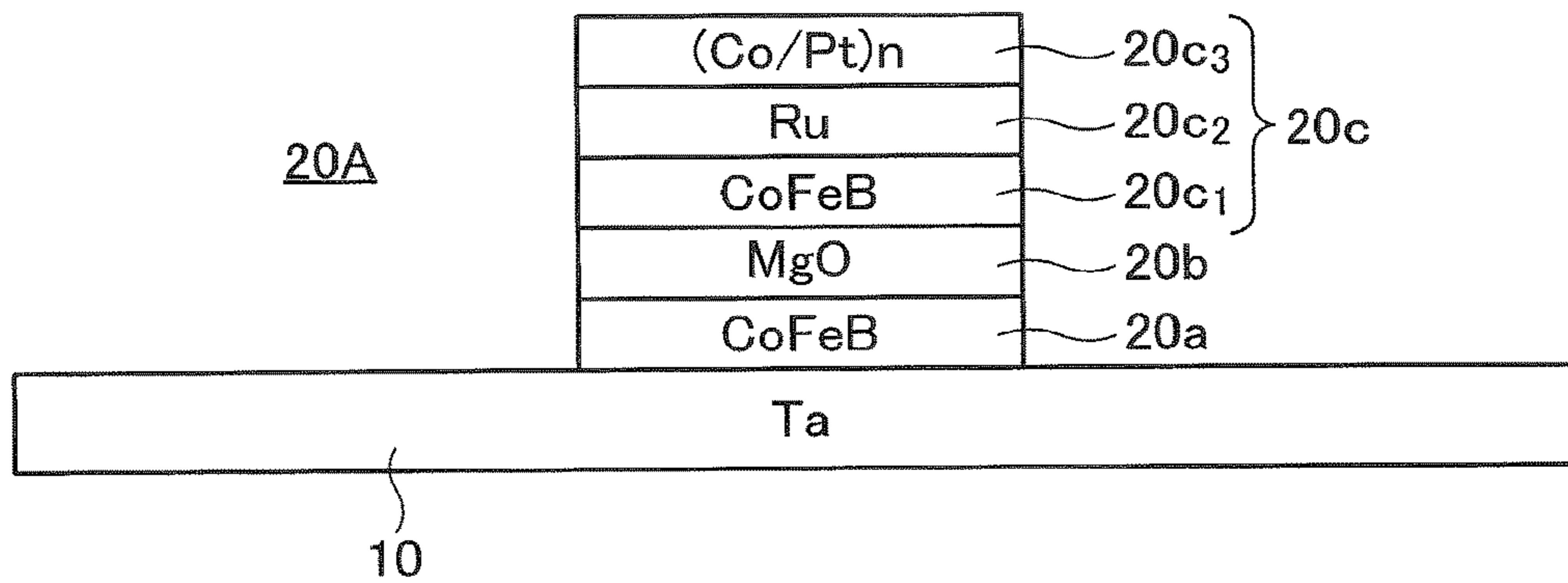


FIG. 12

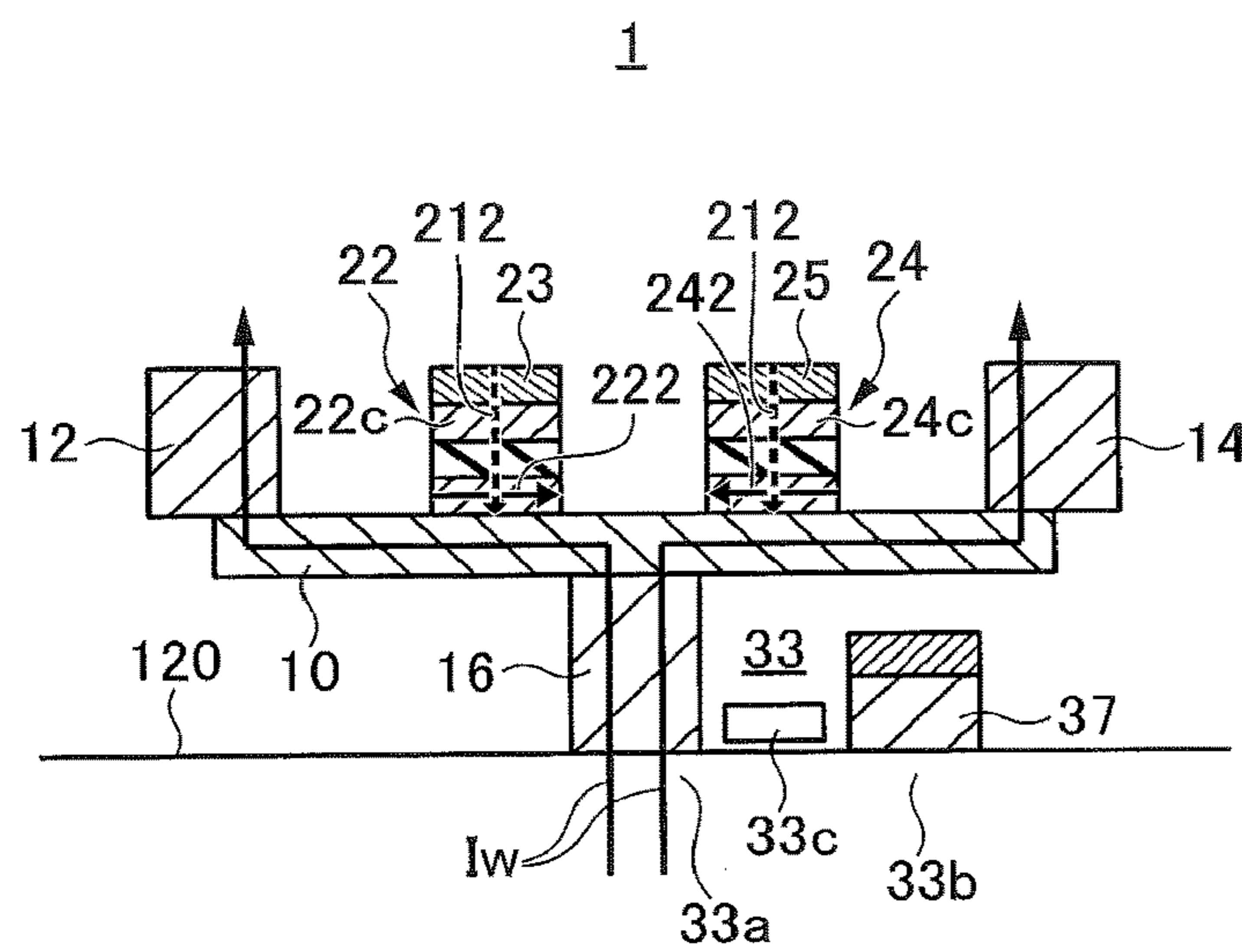


FIG. 13A

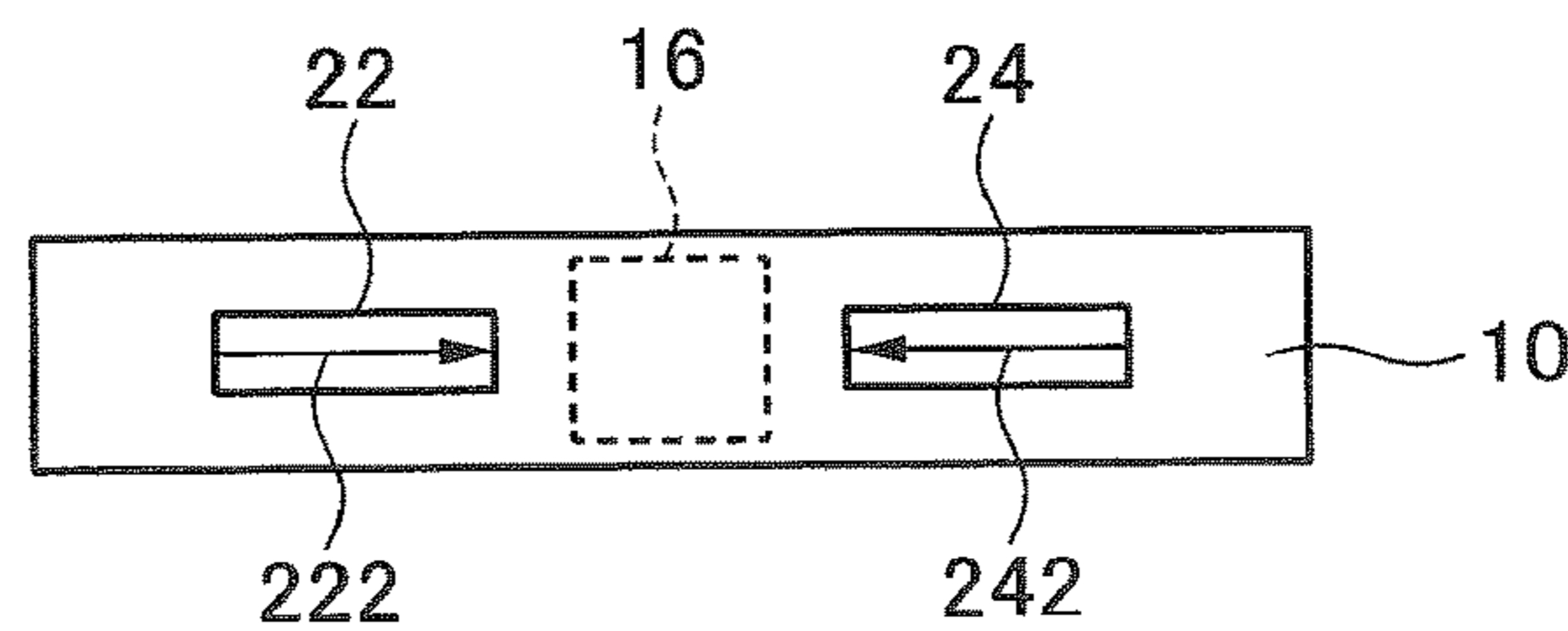


FIG. 13B

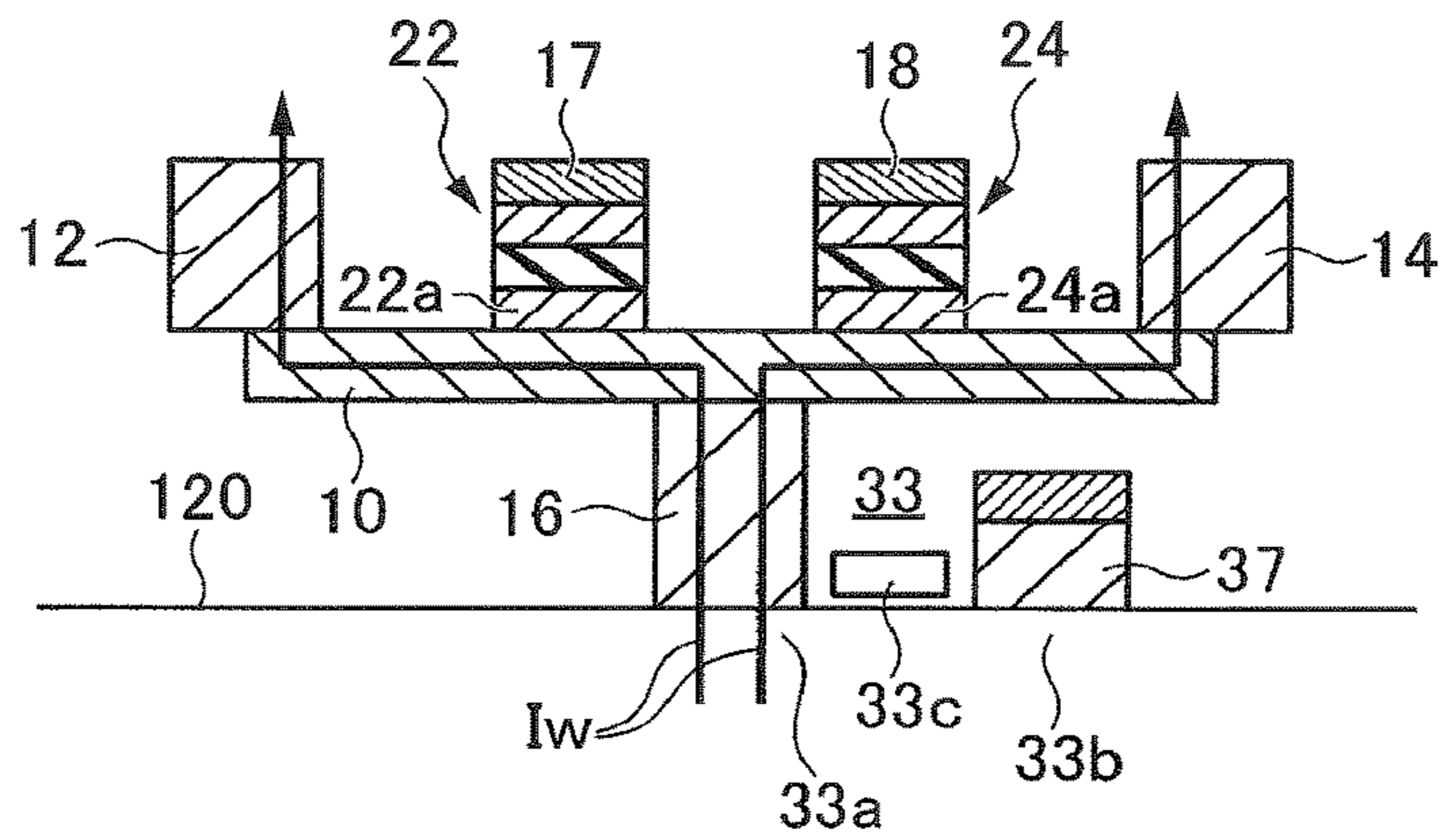


FIG. 14A

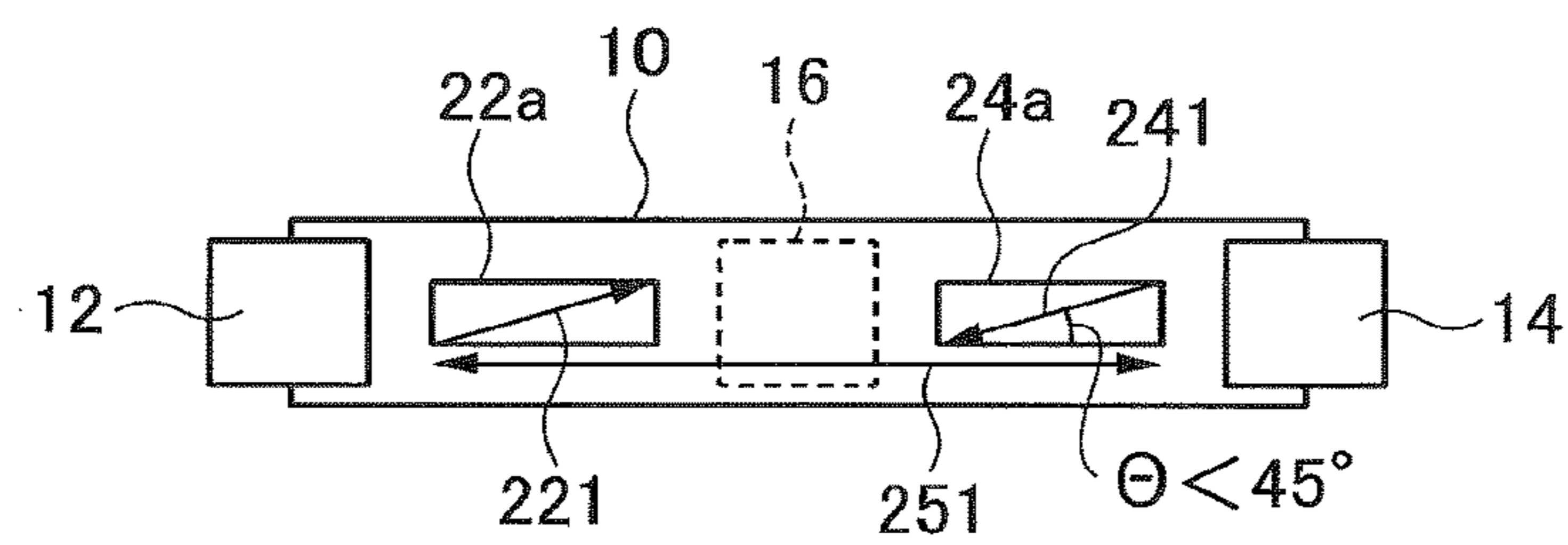


FIG. 14B

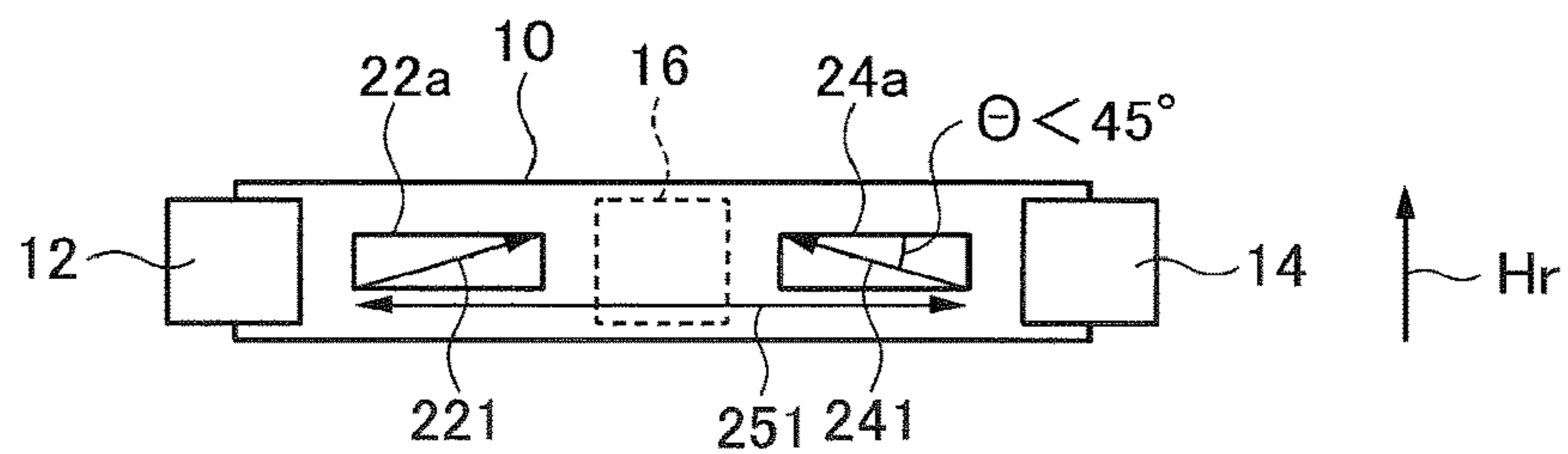


FIG. 14C

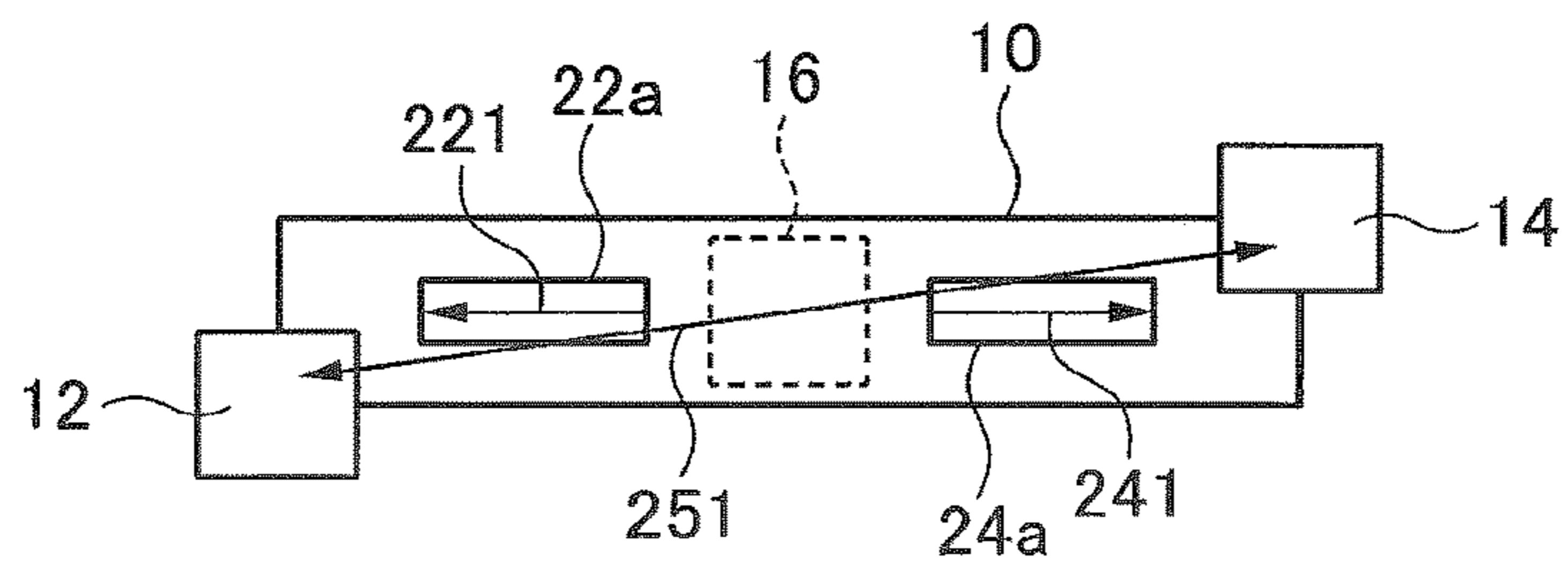


FIG. 14D

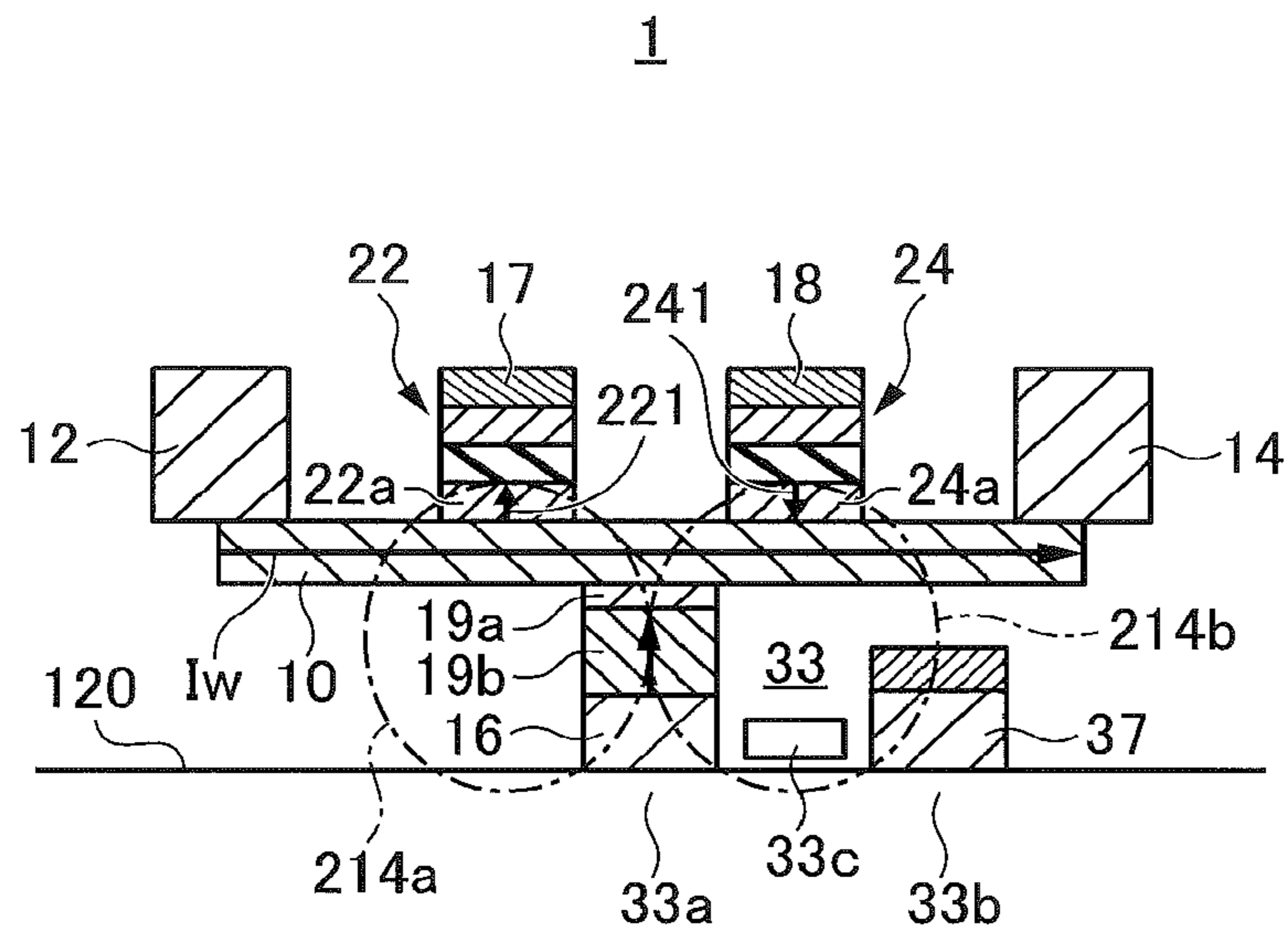


FIG. 15A

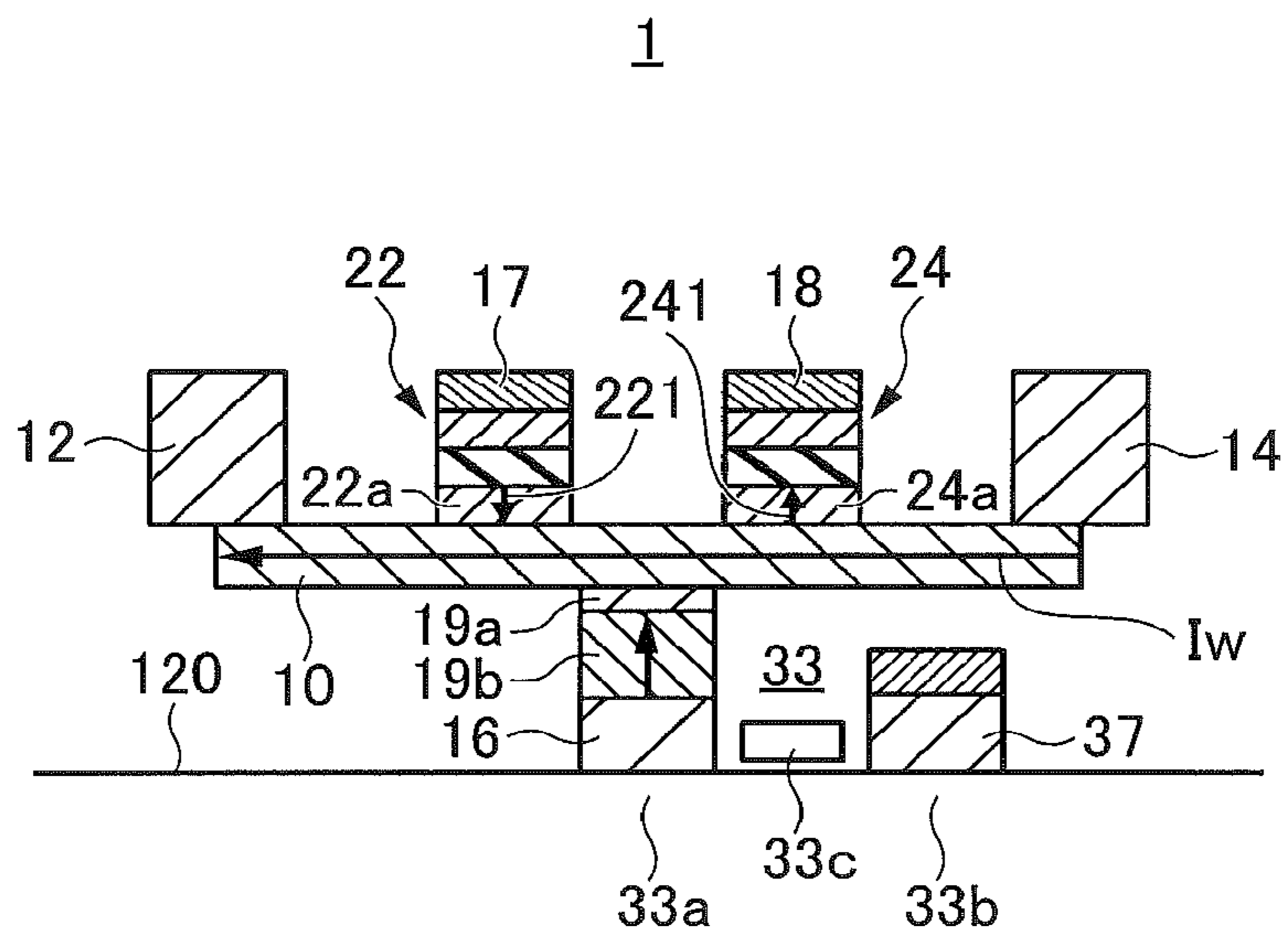


FIG. 15B

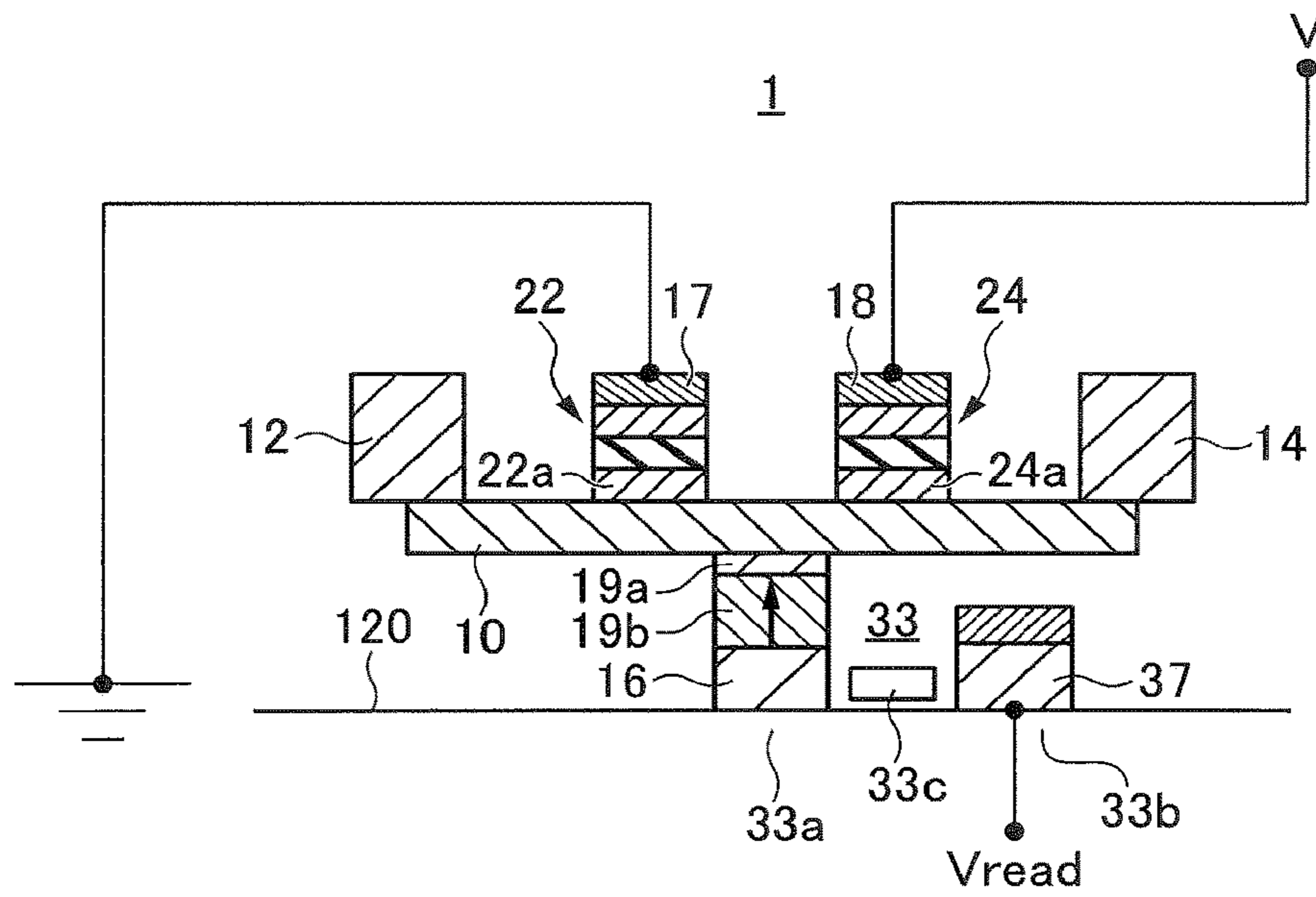


FIG. 15C

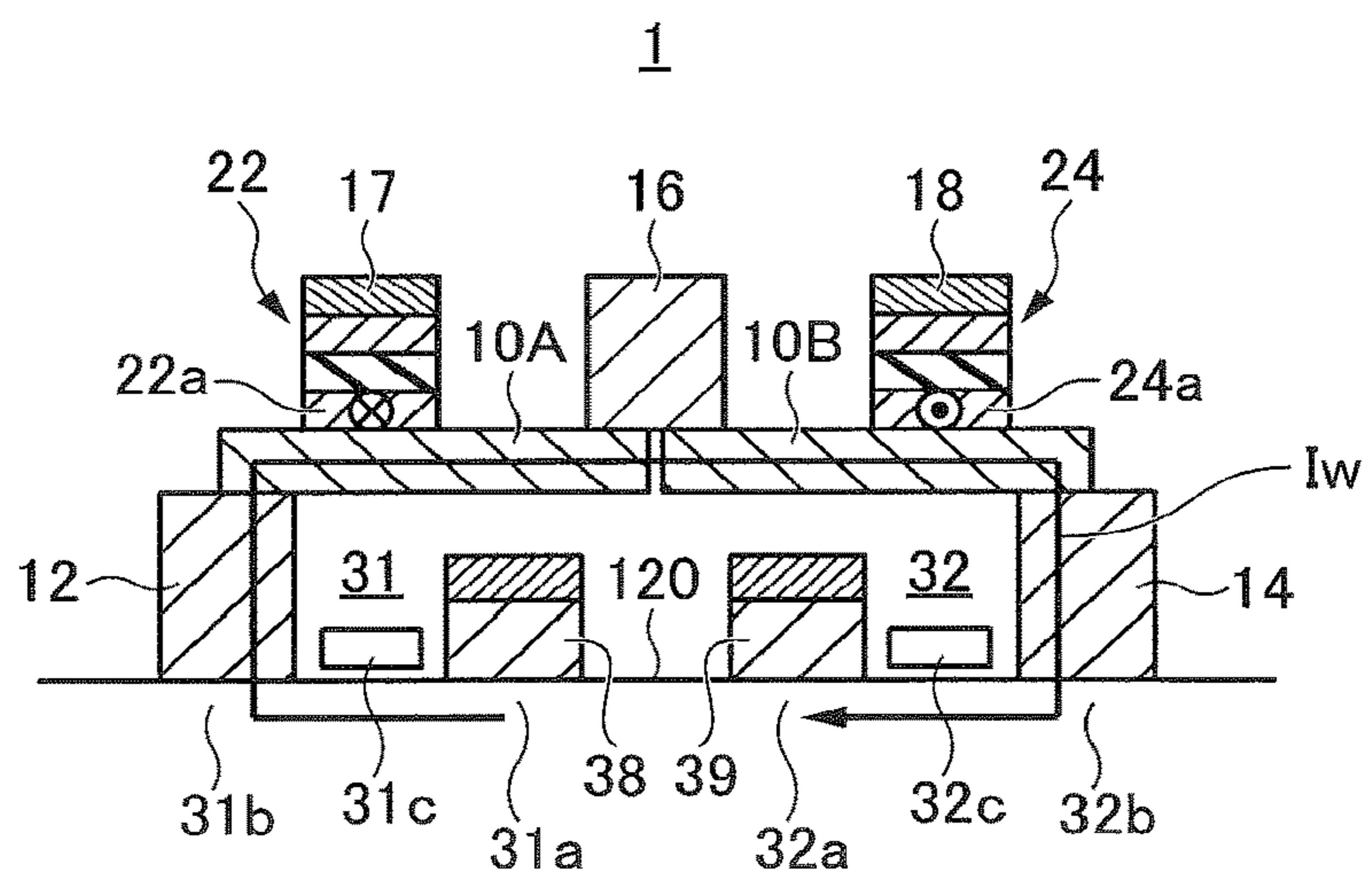


FIG. 16A

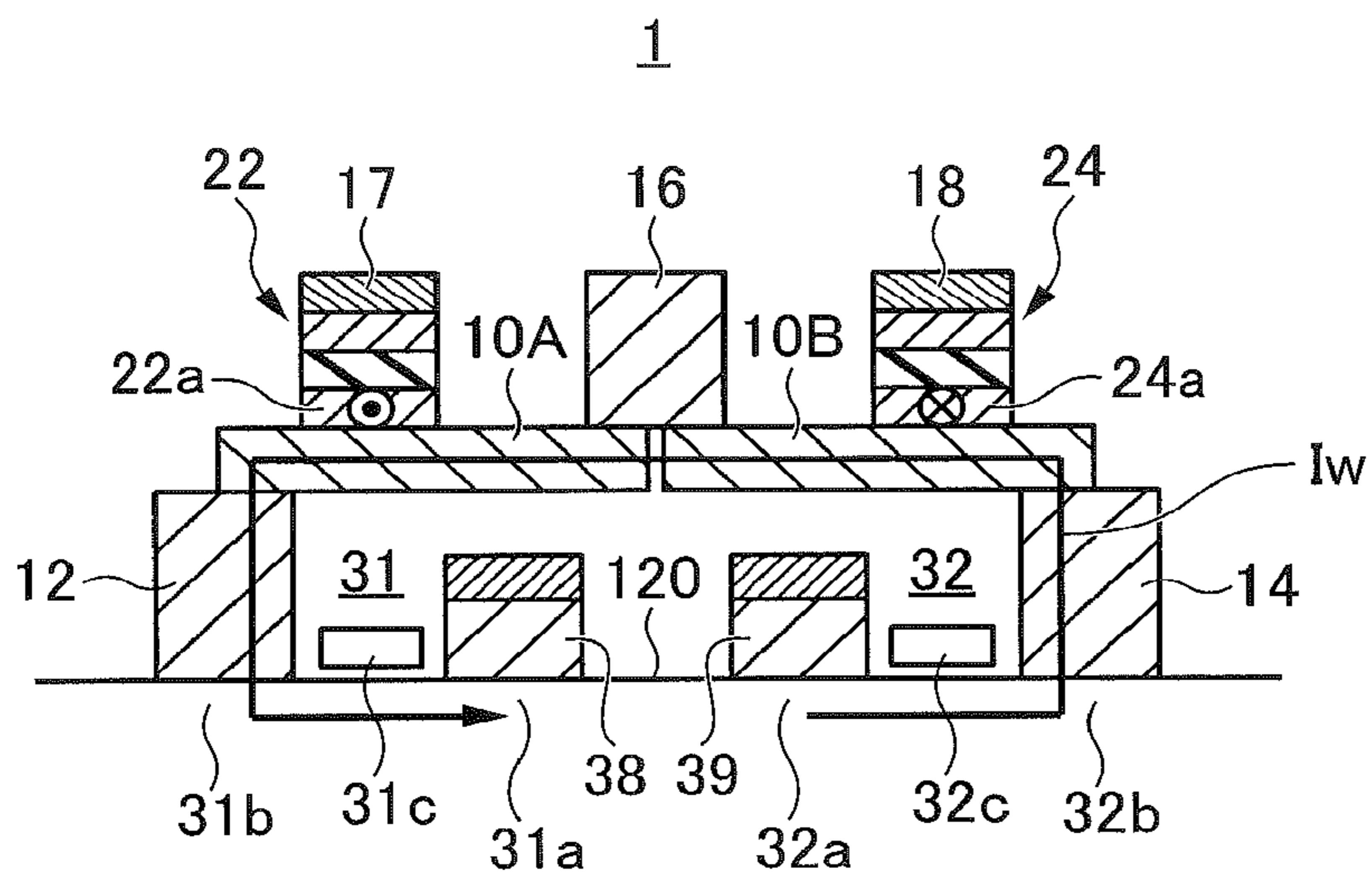


FIG. 16B

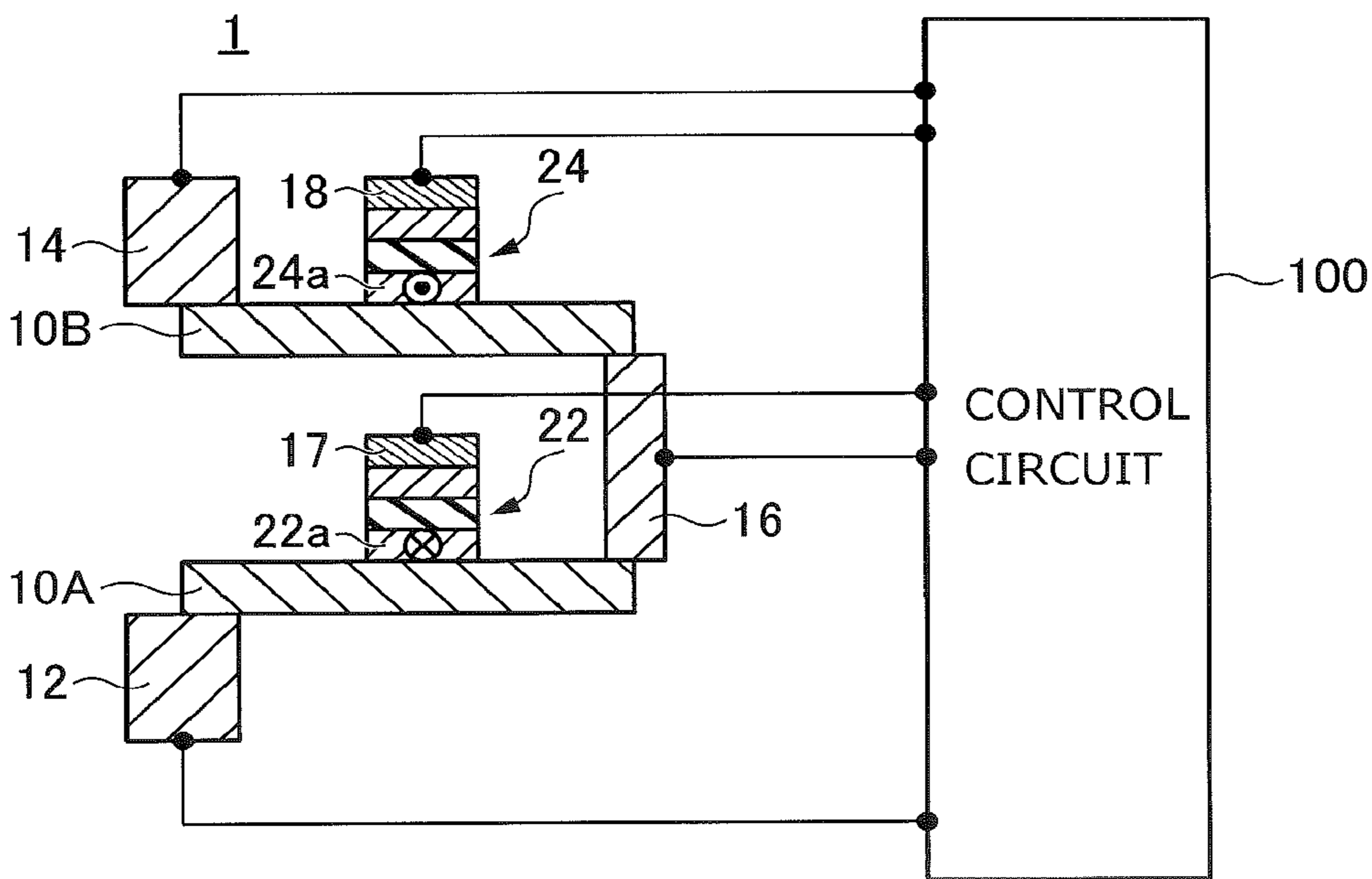


FIG. 17

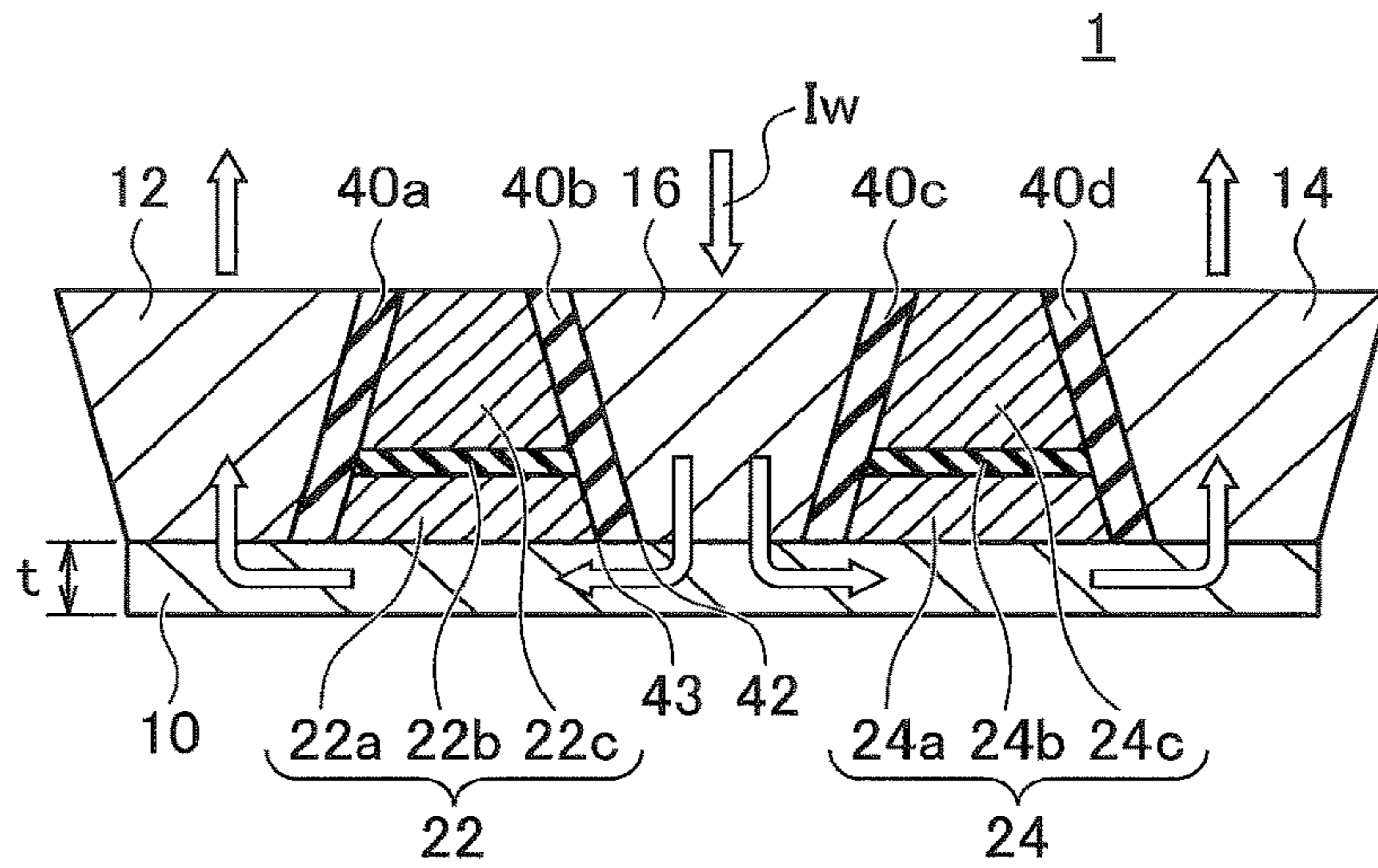


FIG. 18

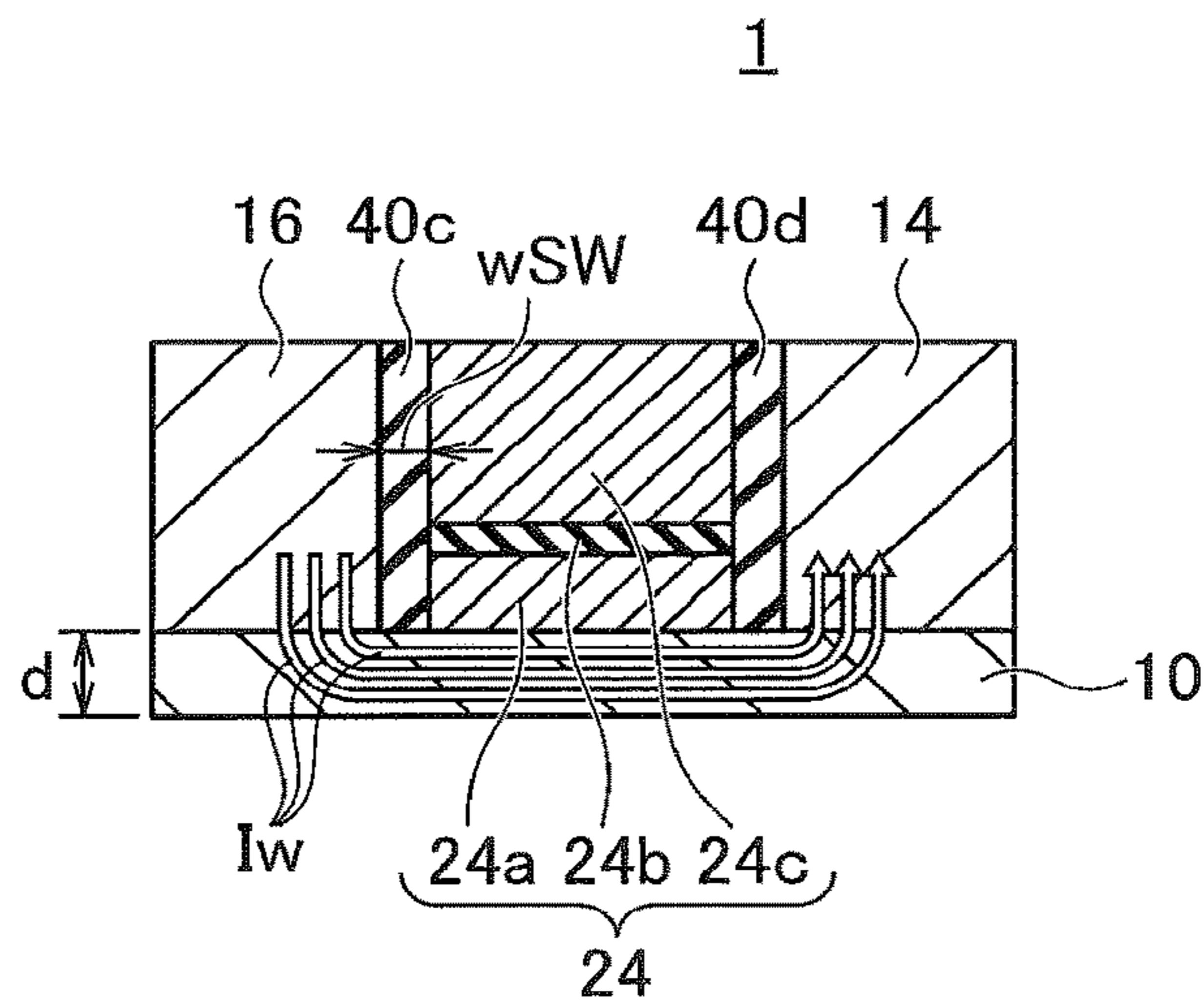


FIG. 19

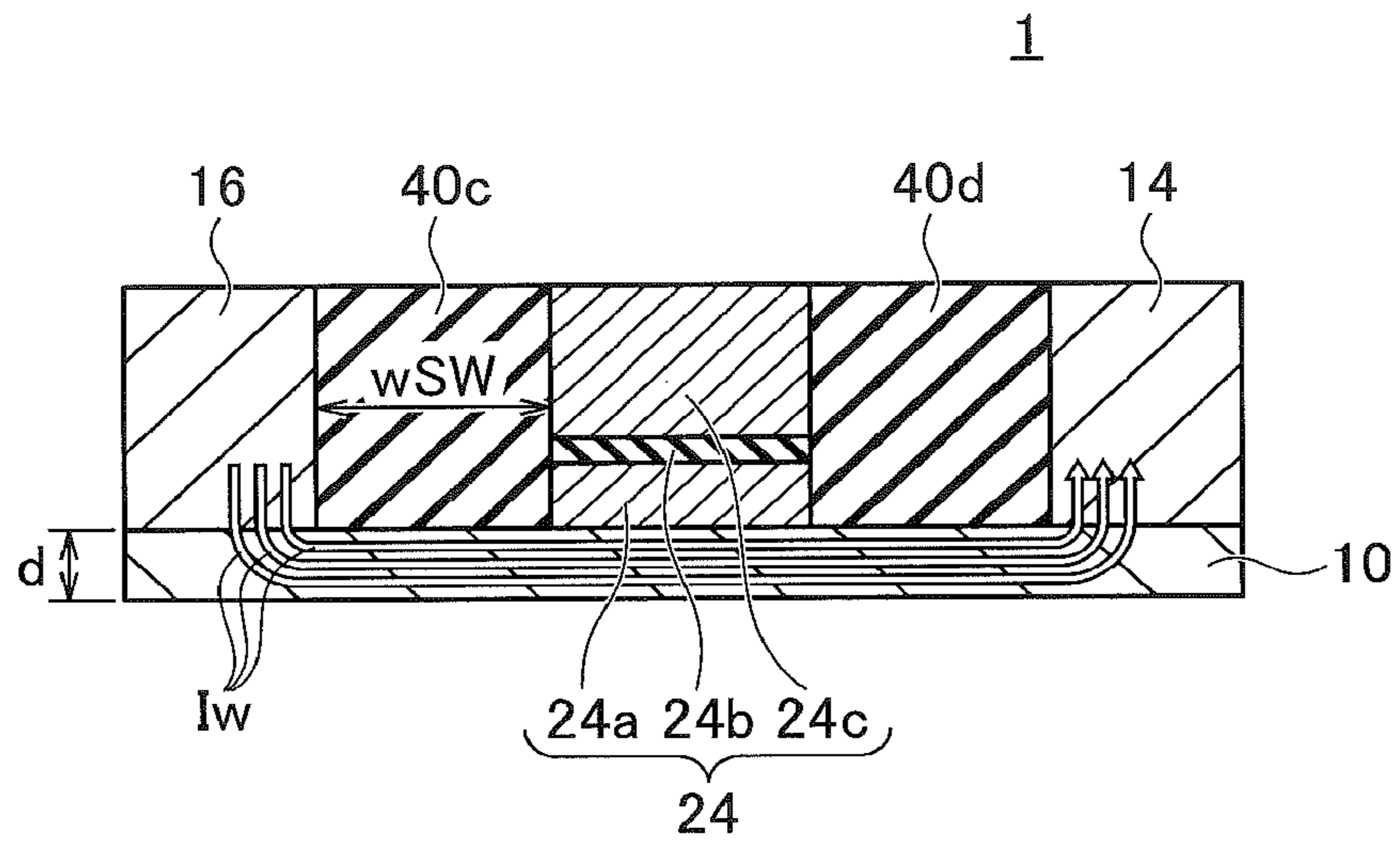


FIG. 20

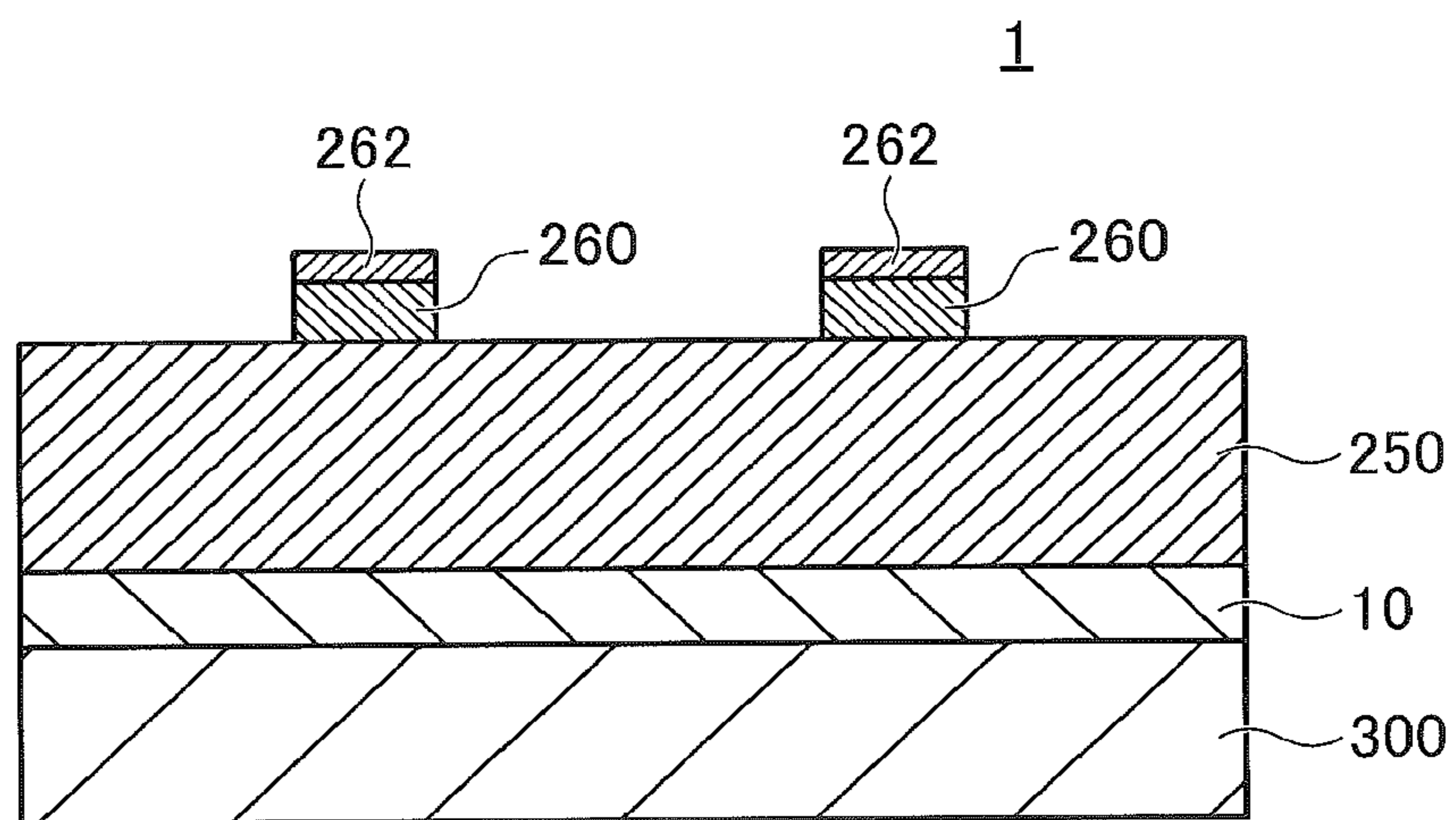


FIG. 21

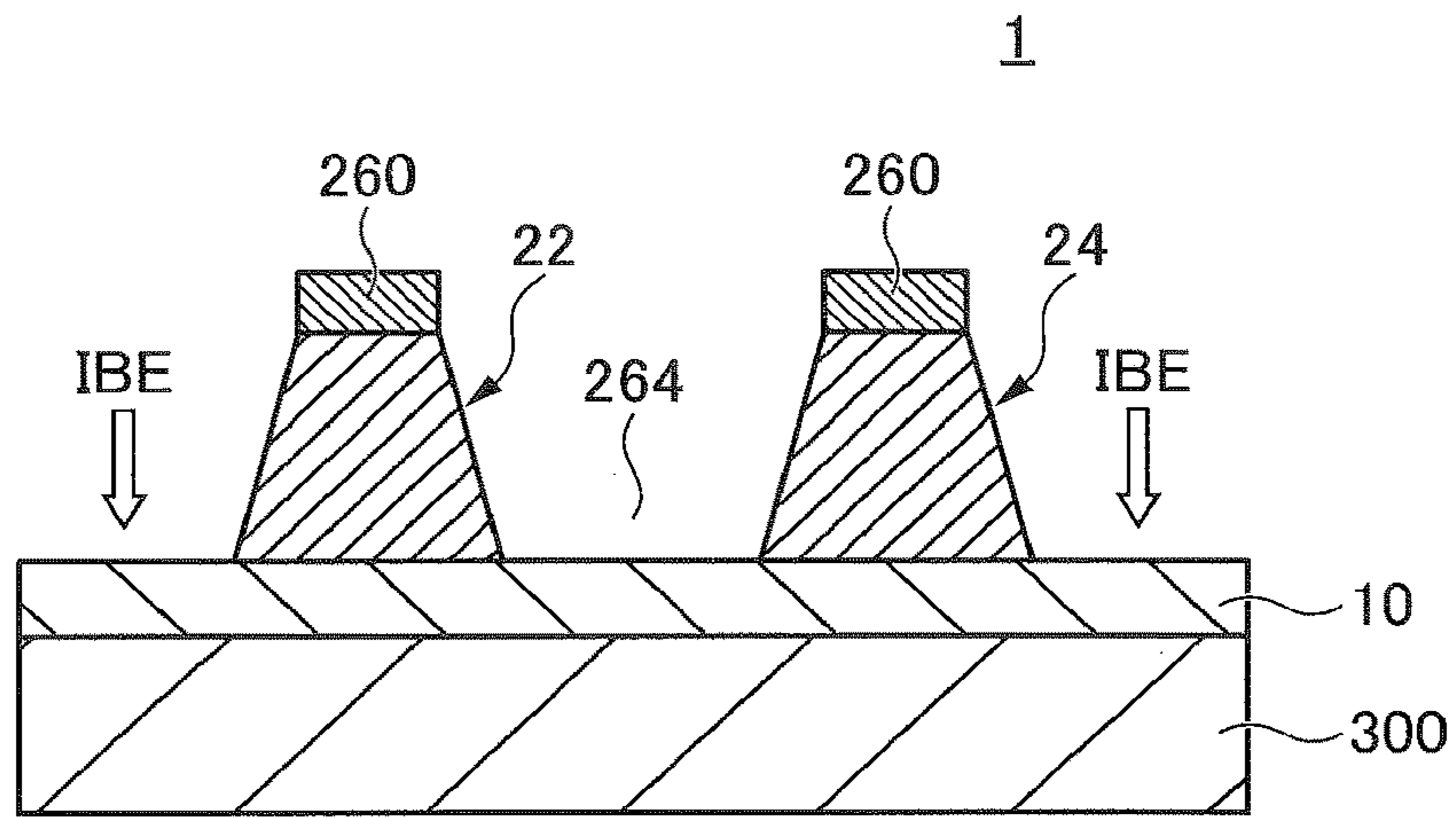


FIG. 22

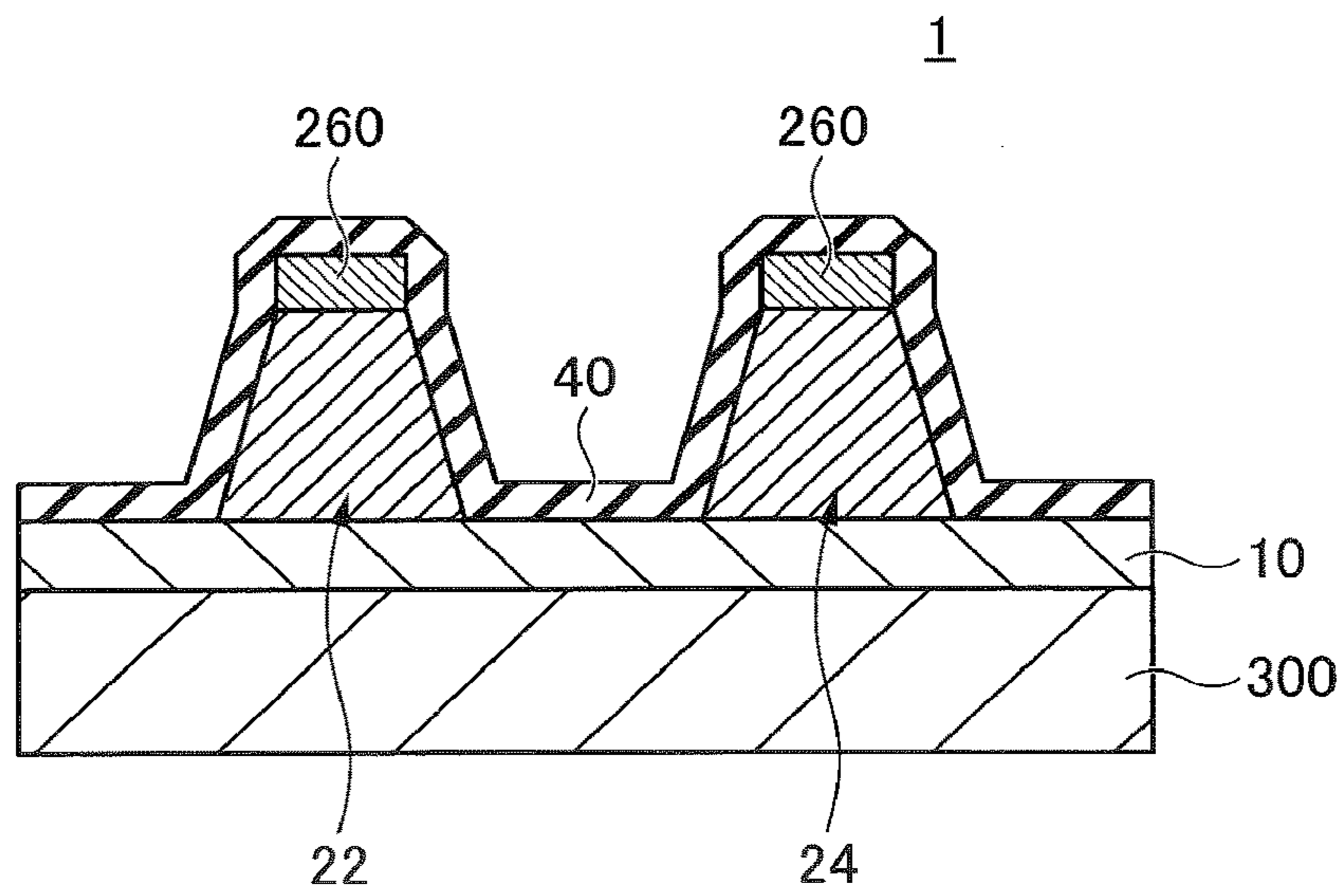


FIG. 23



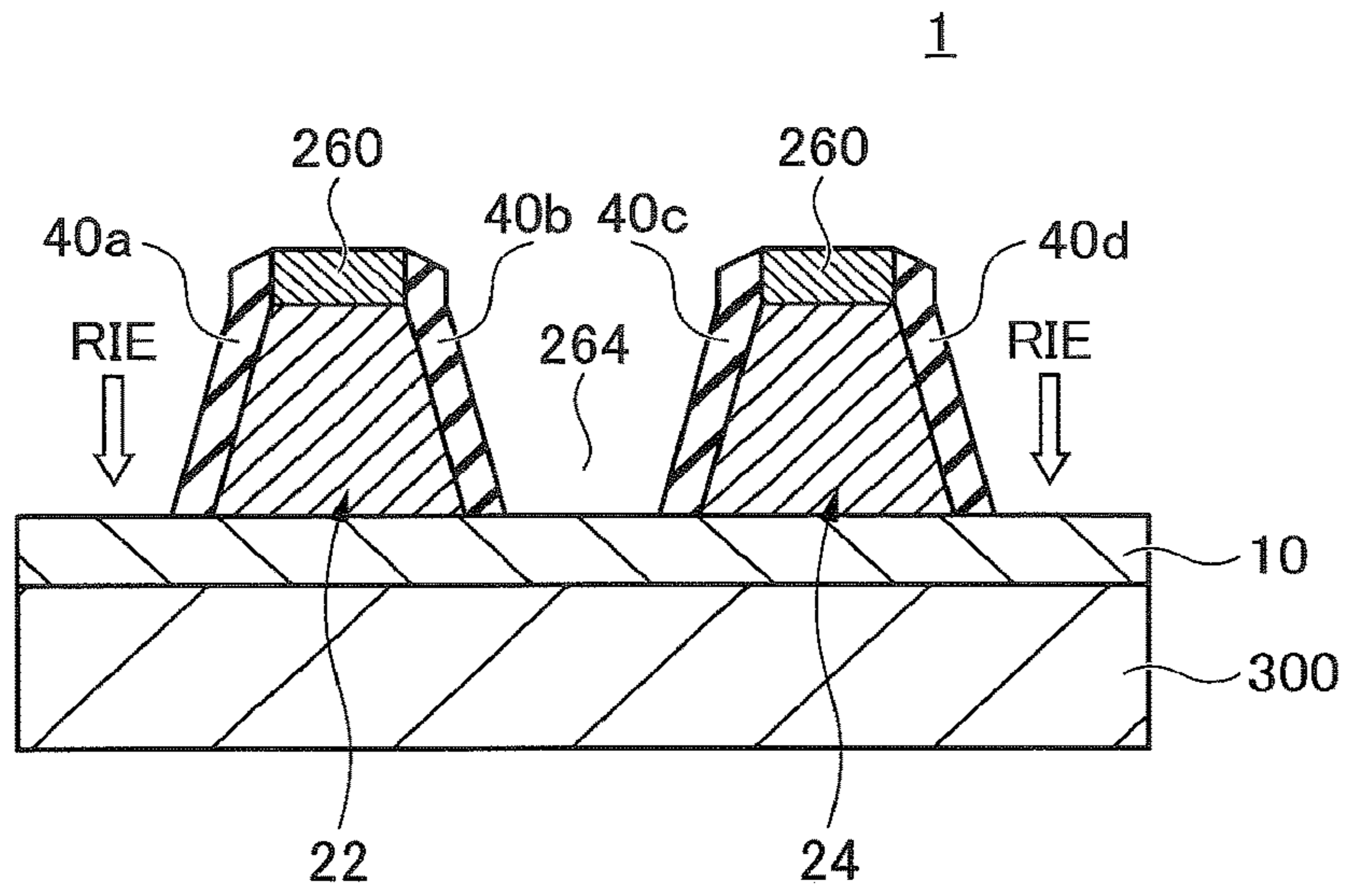


FIG. 24

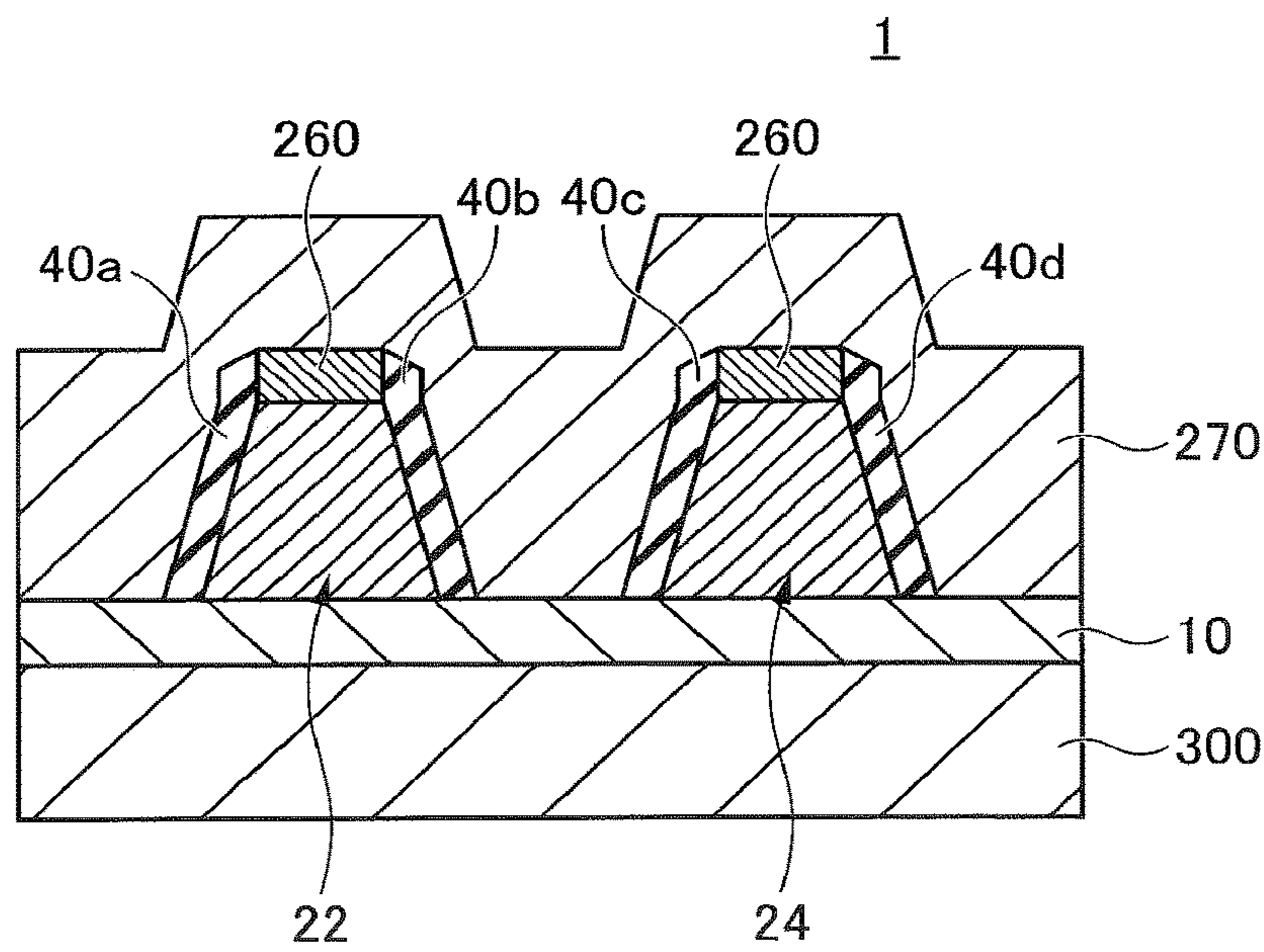


FIG. 25

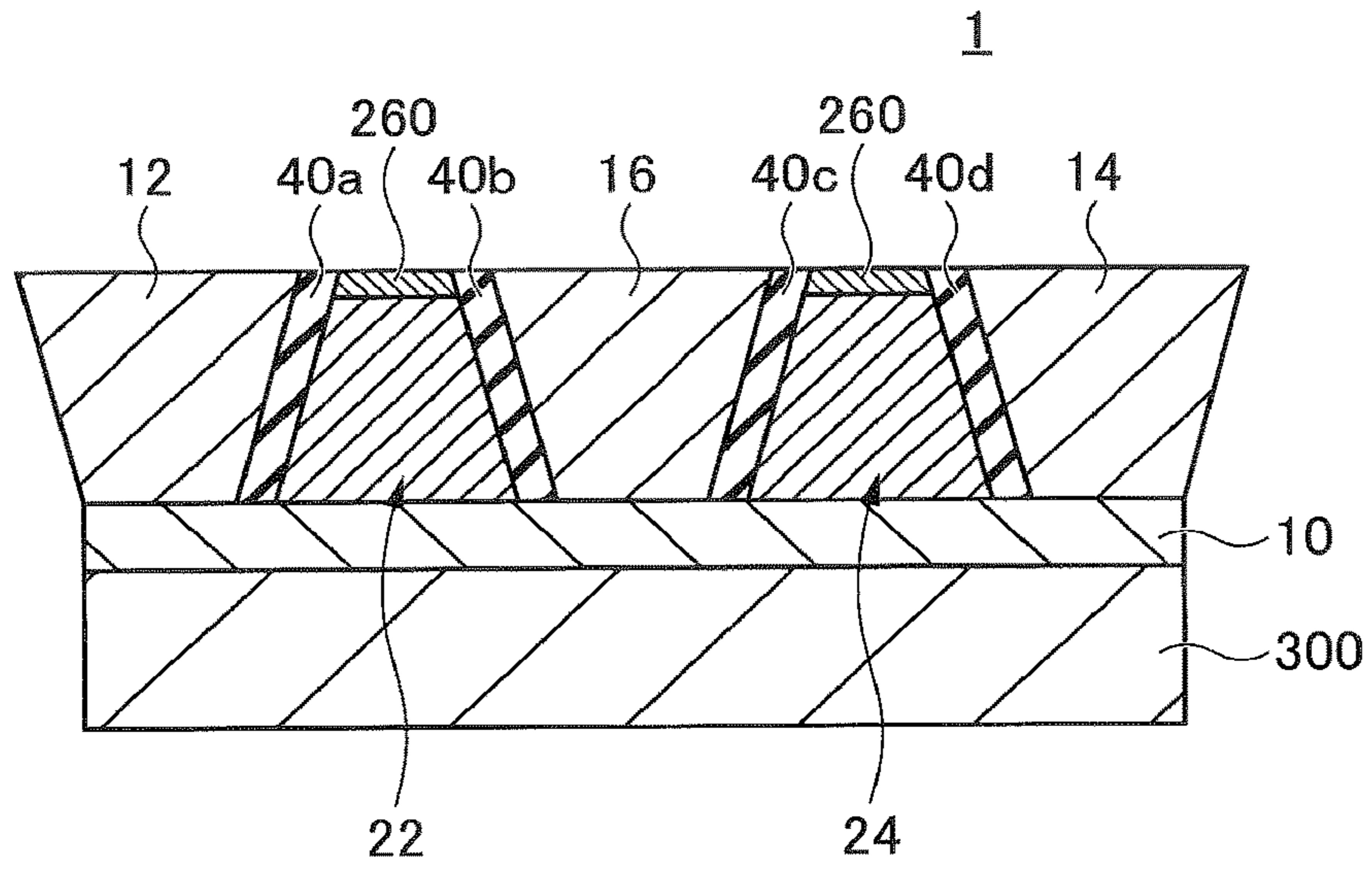


FIG. 26

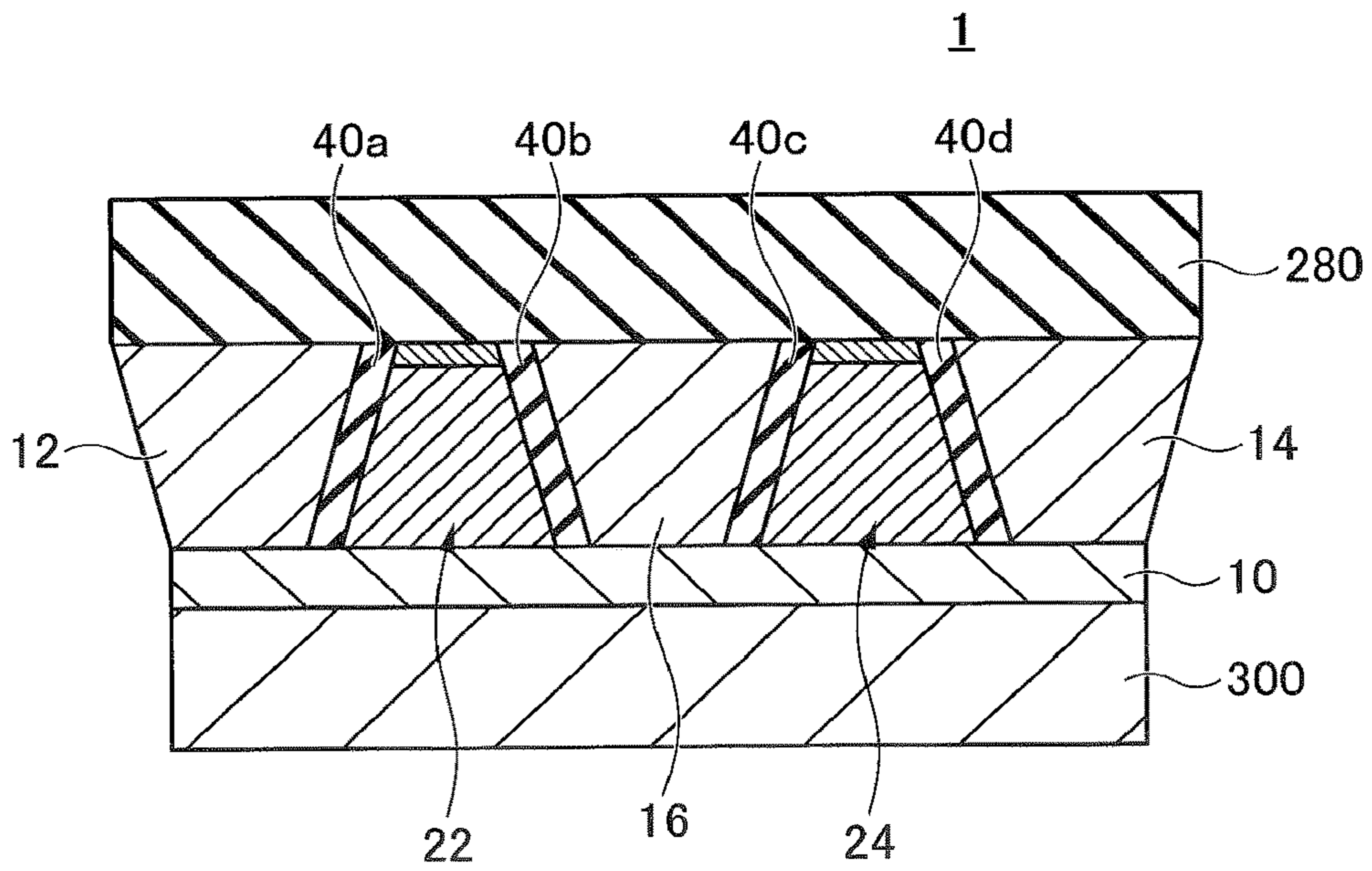


FIG. 27

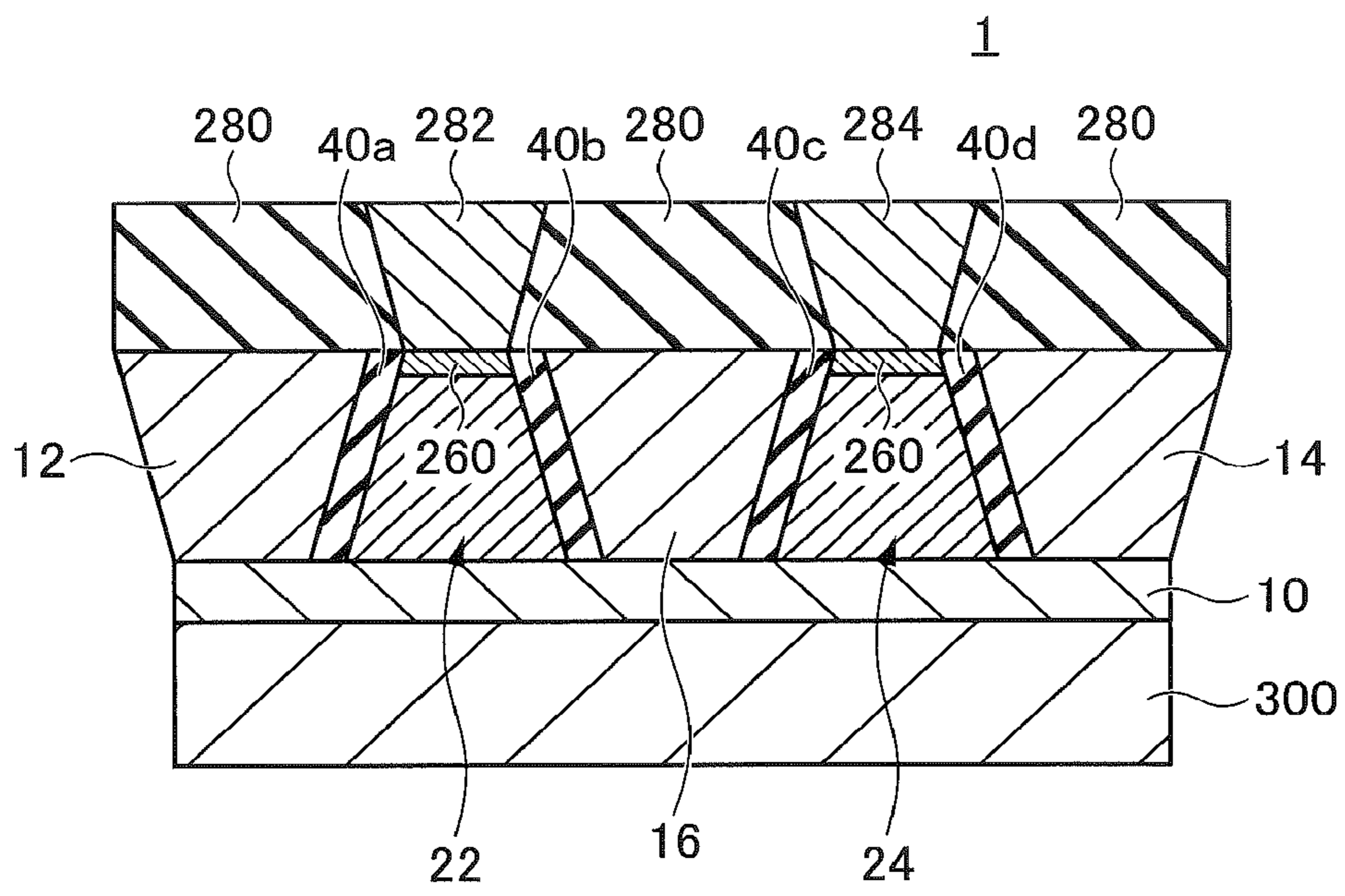


FIG. 28

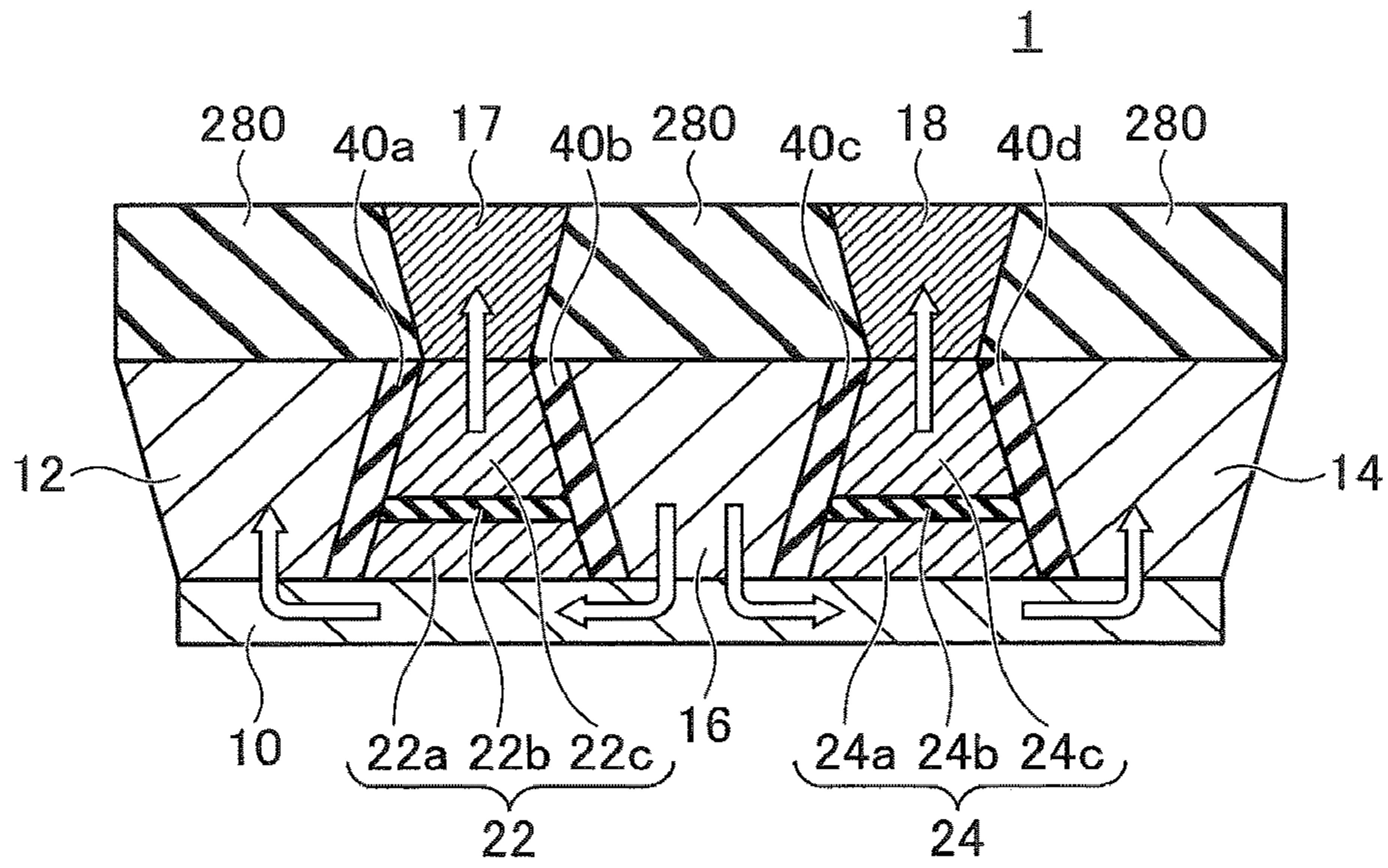


FIG. 29

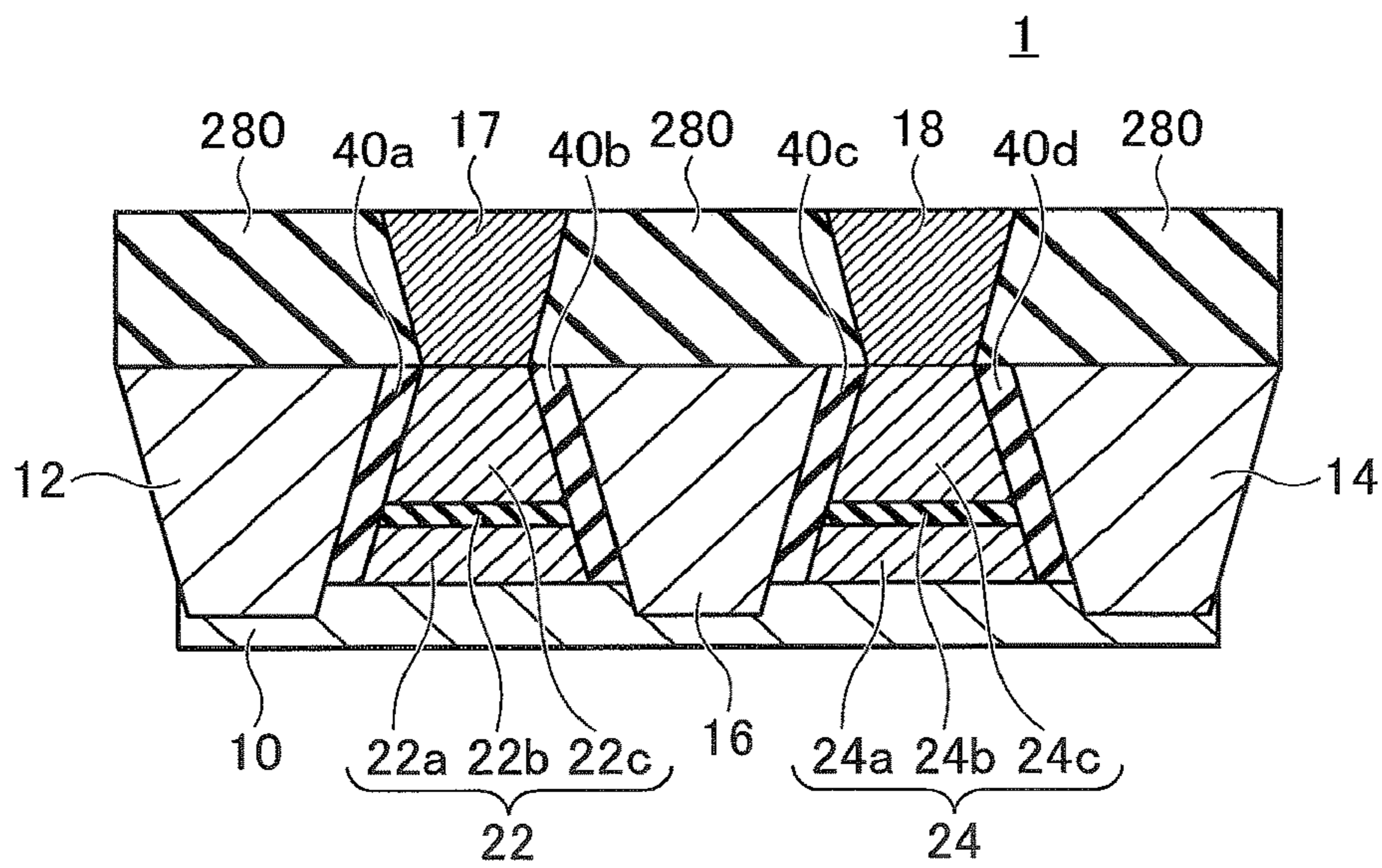


FIG. 30

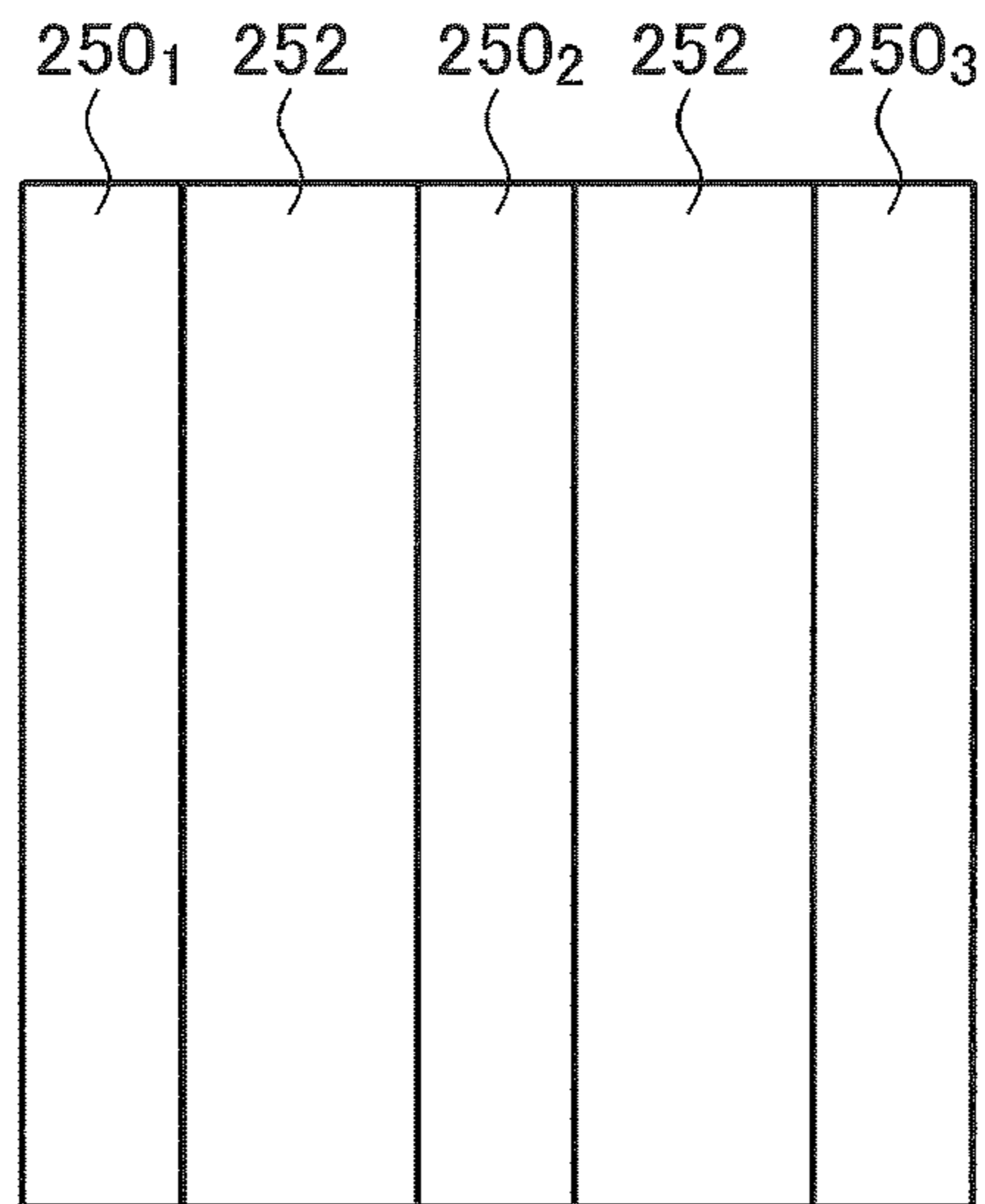


FIG. 31A

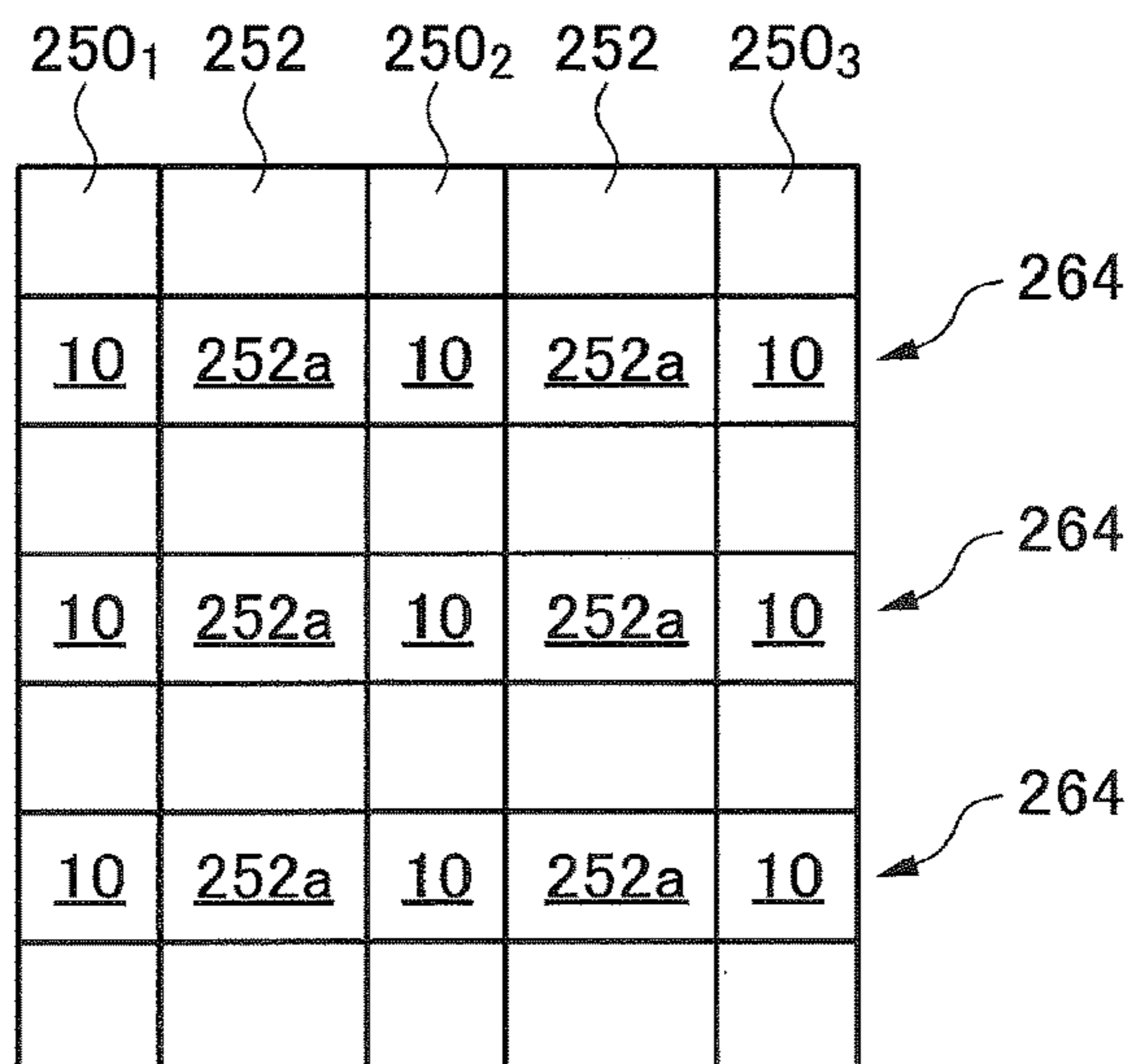


FIG. 31B

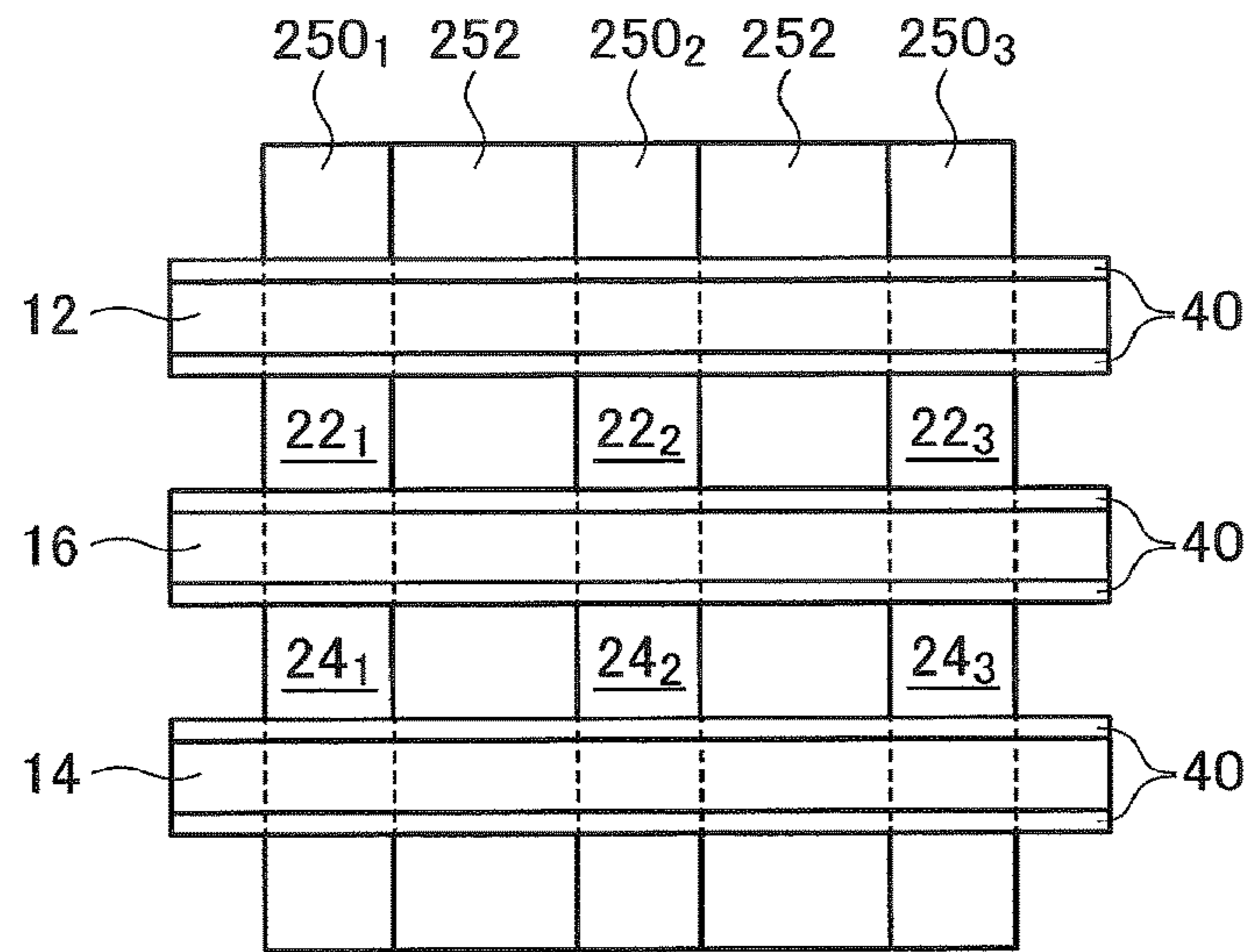


FIG. 31C

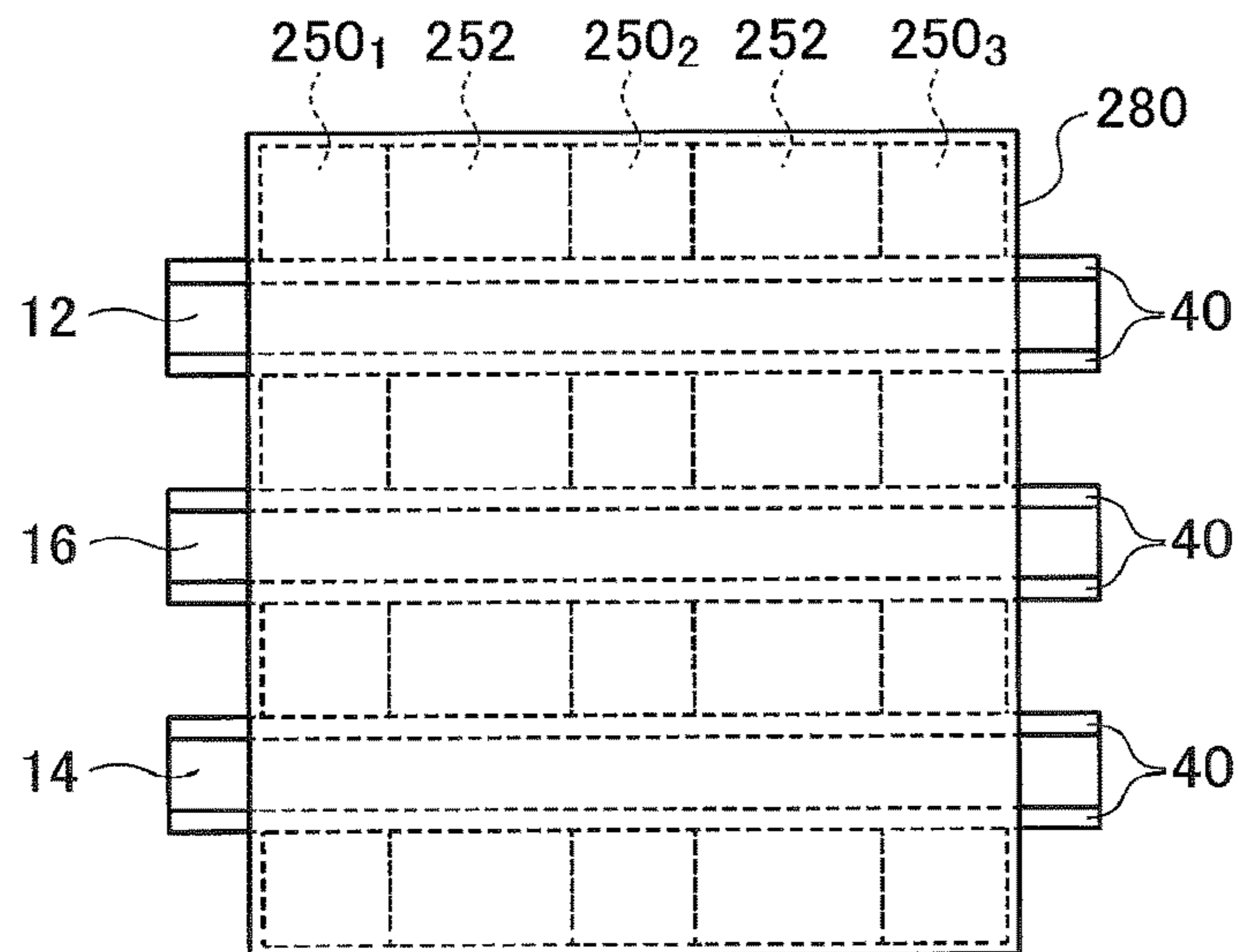


FIG. 31D

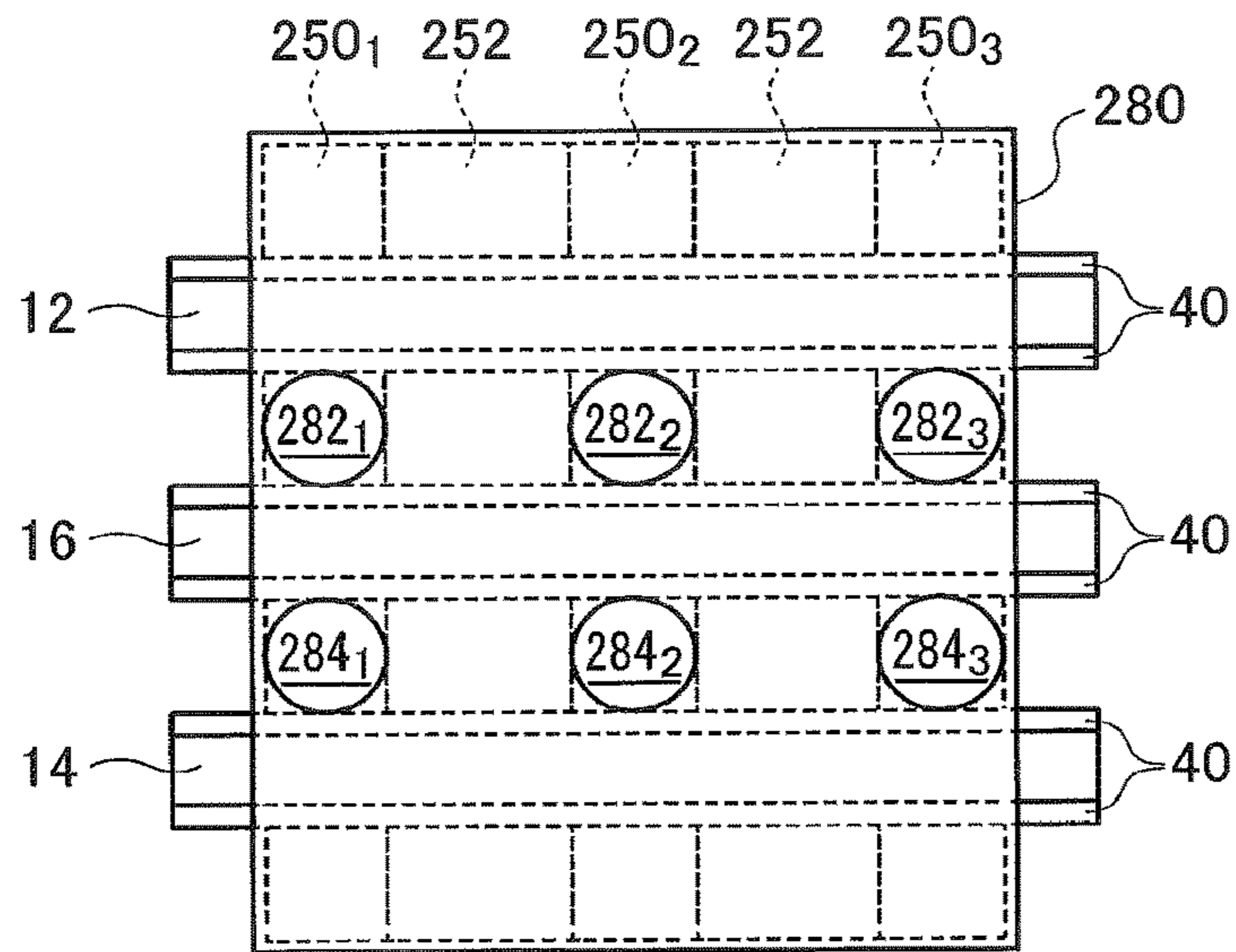


FIG. 31E

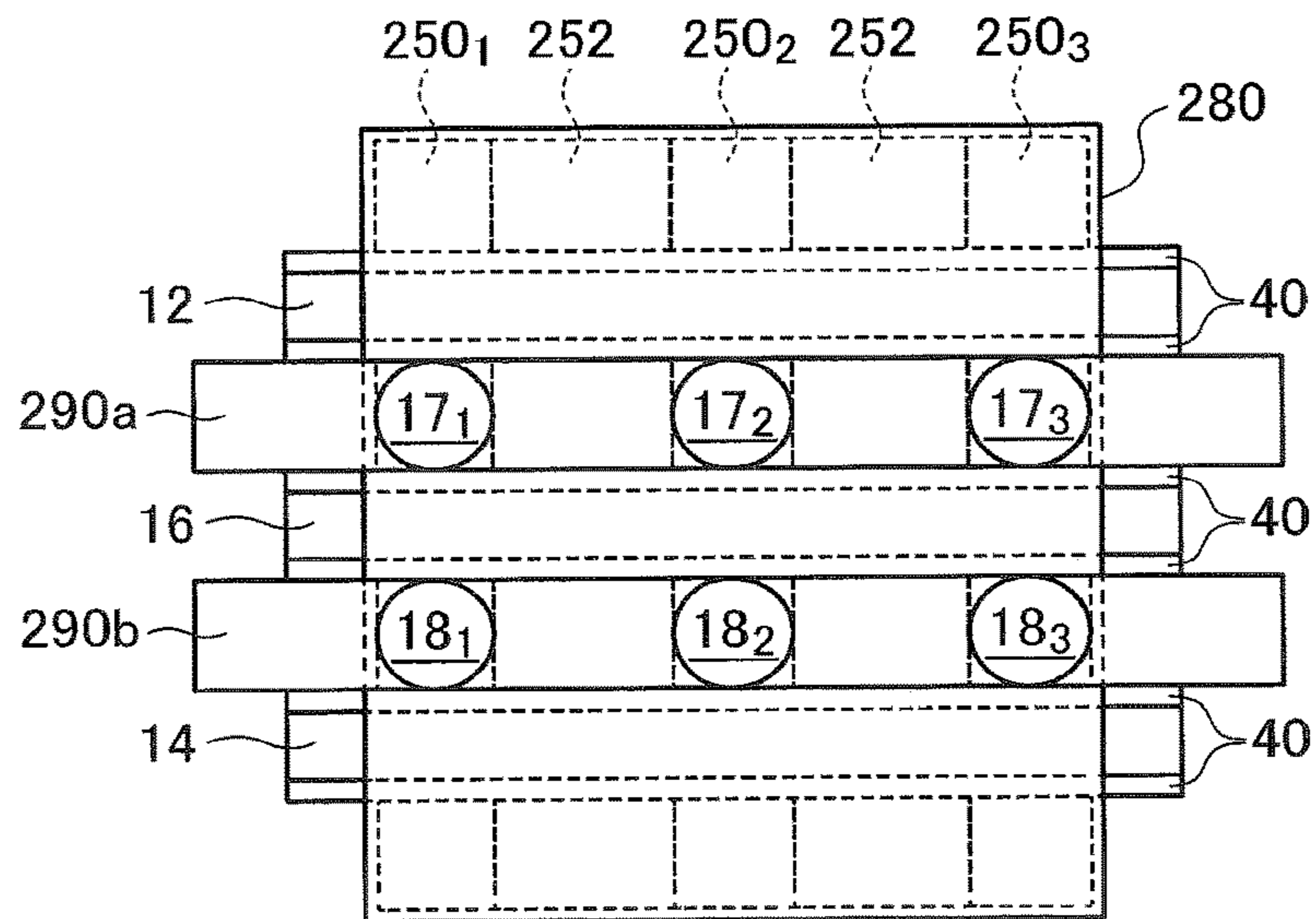


FIG. 31F

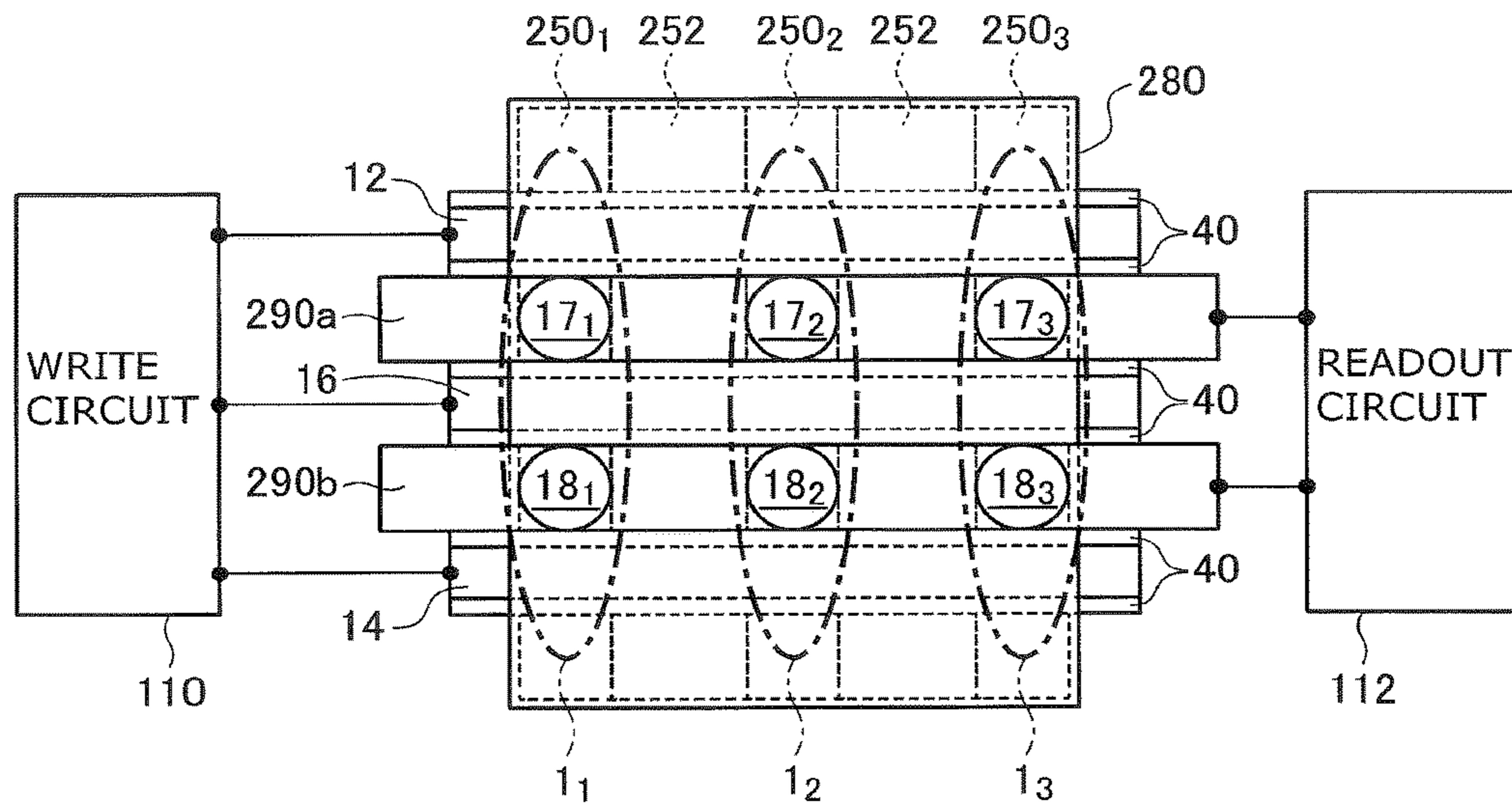


FIG. 32

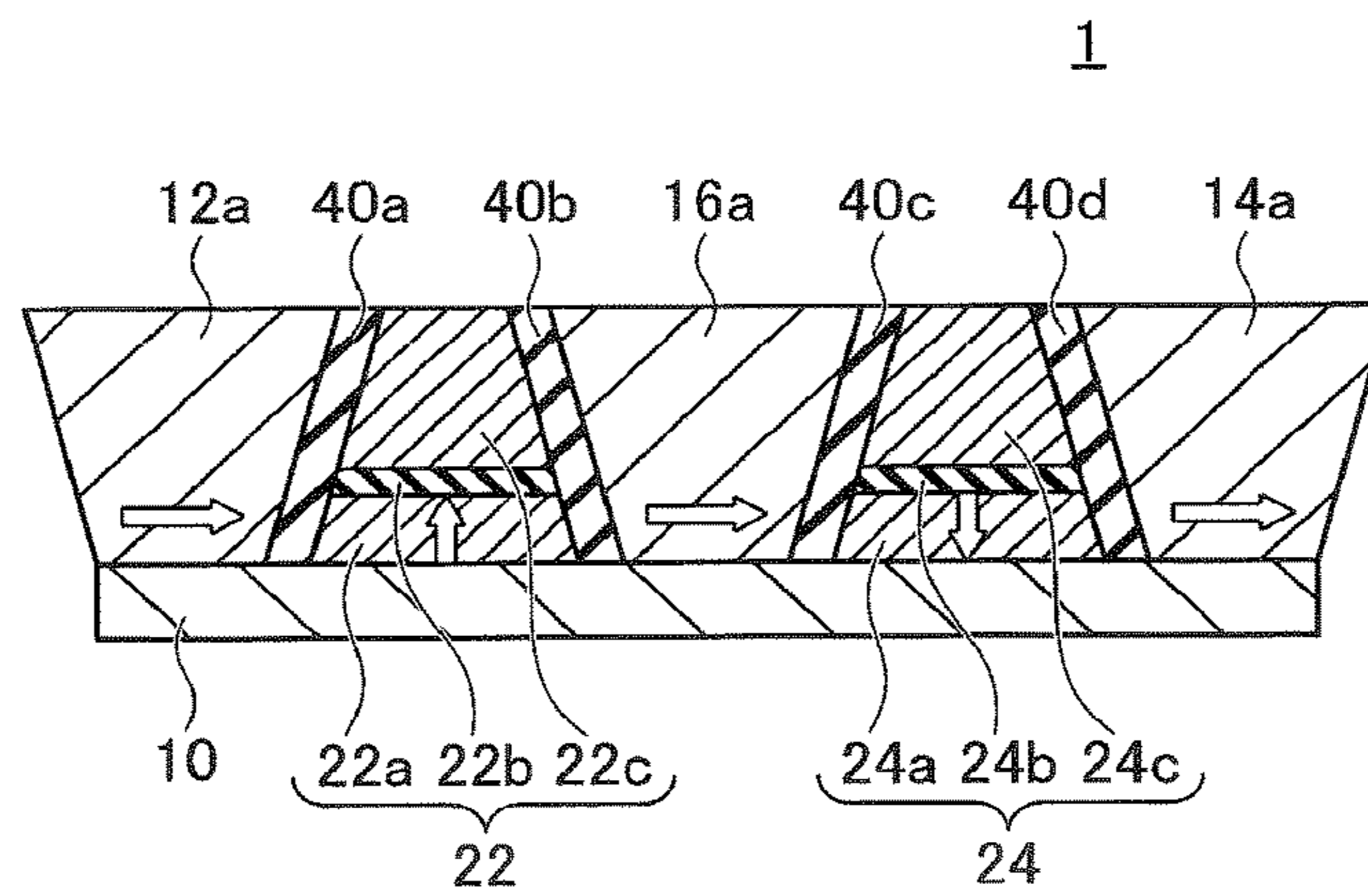


FIG. 33



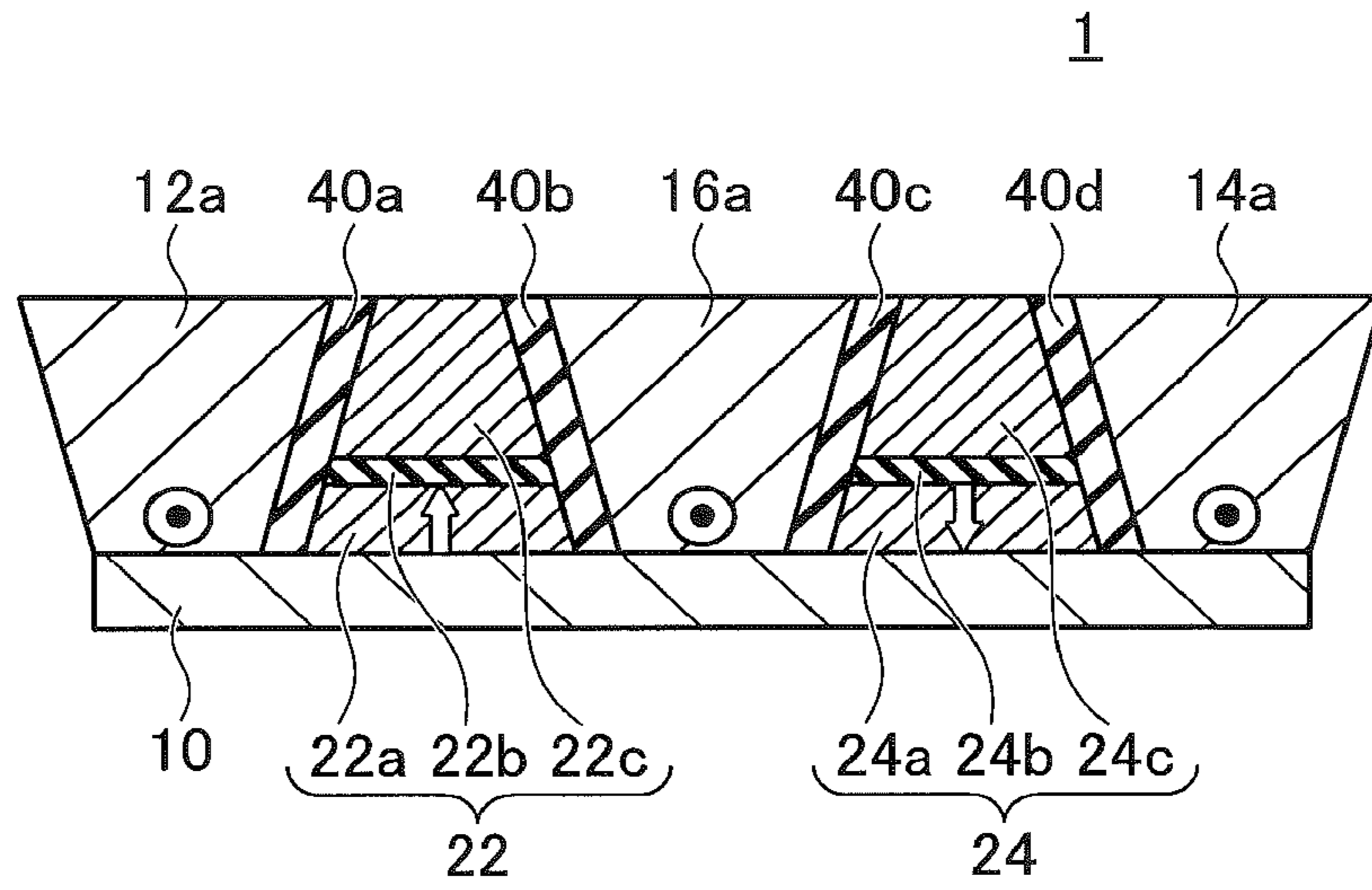


FIG. 34

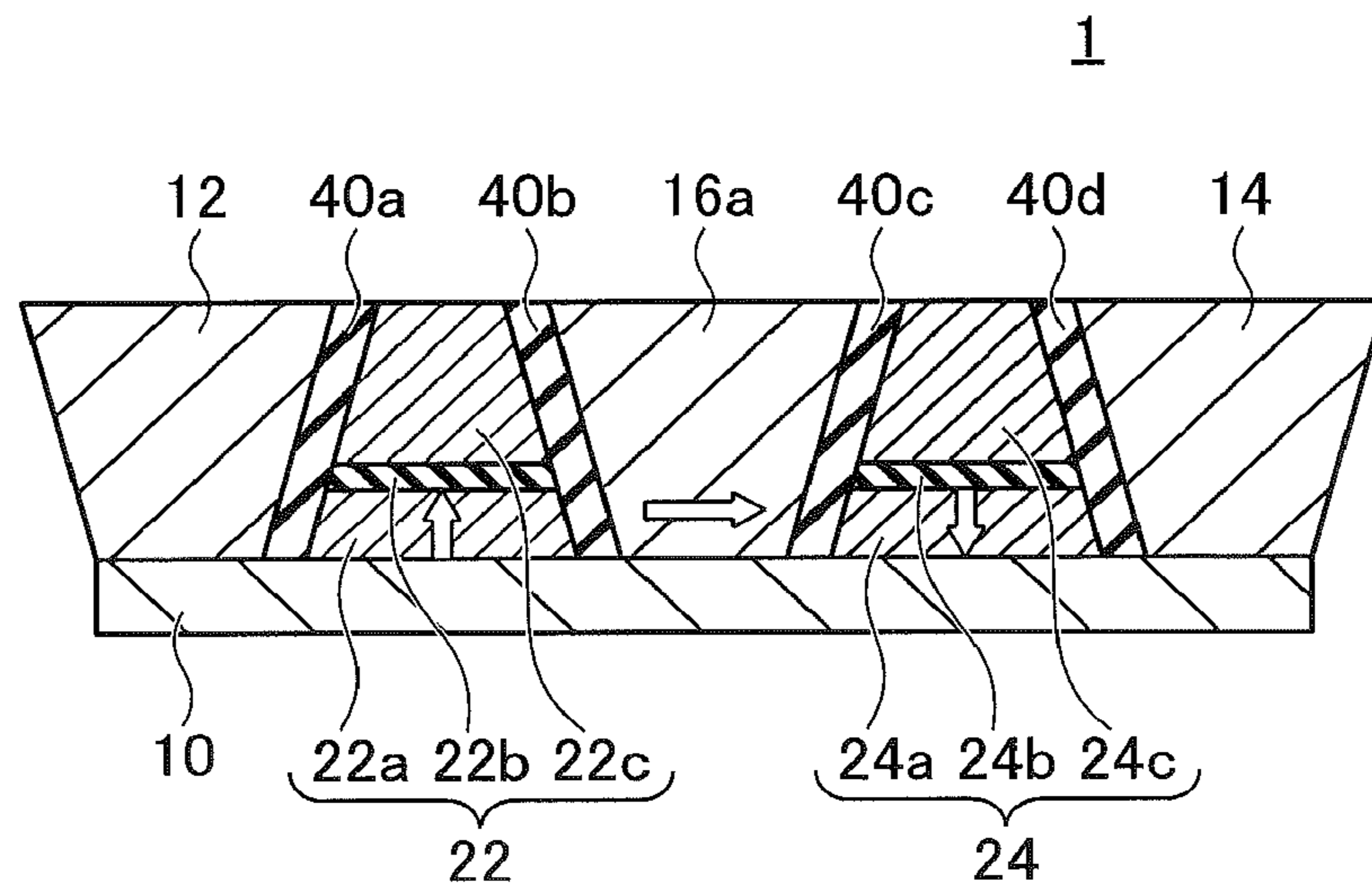


FIG. 35

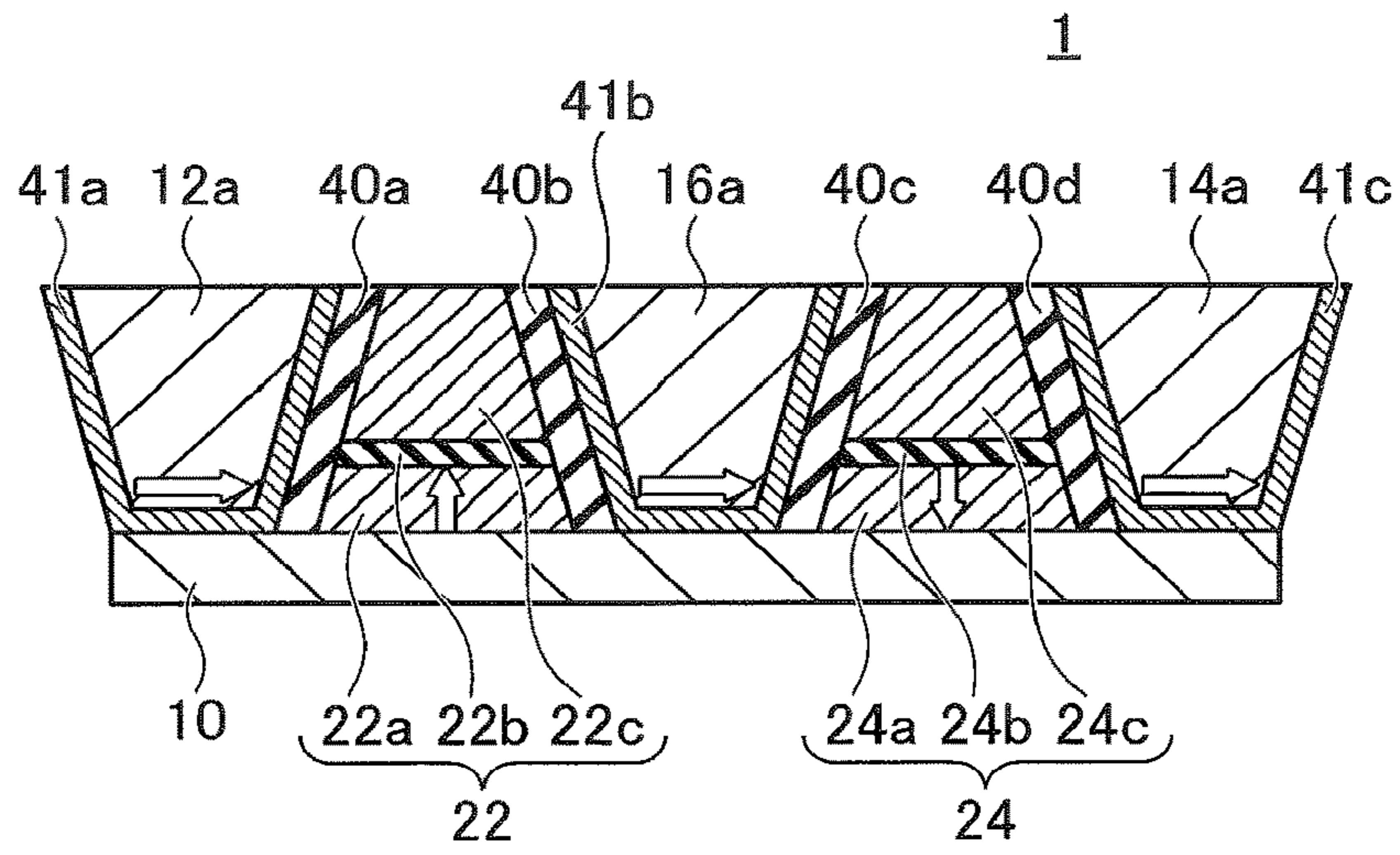


FIG. 36

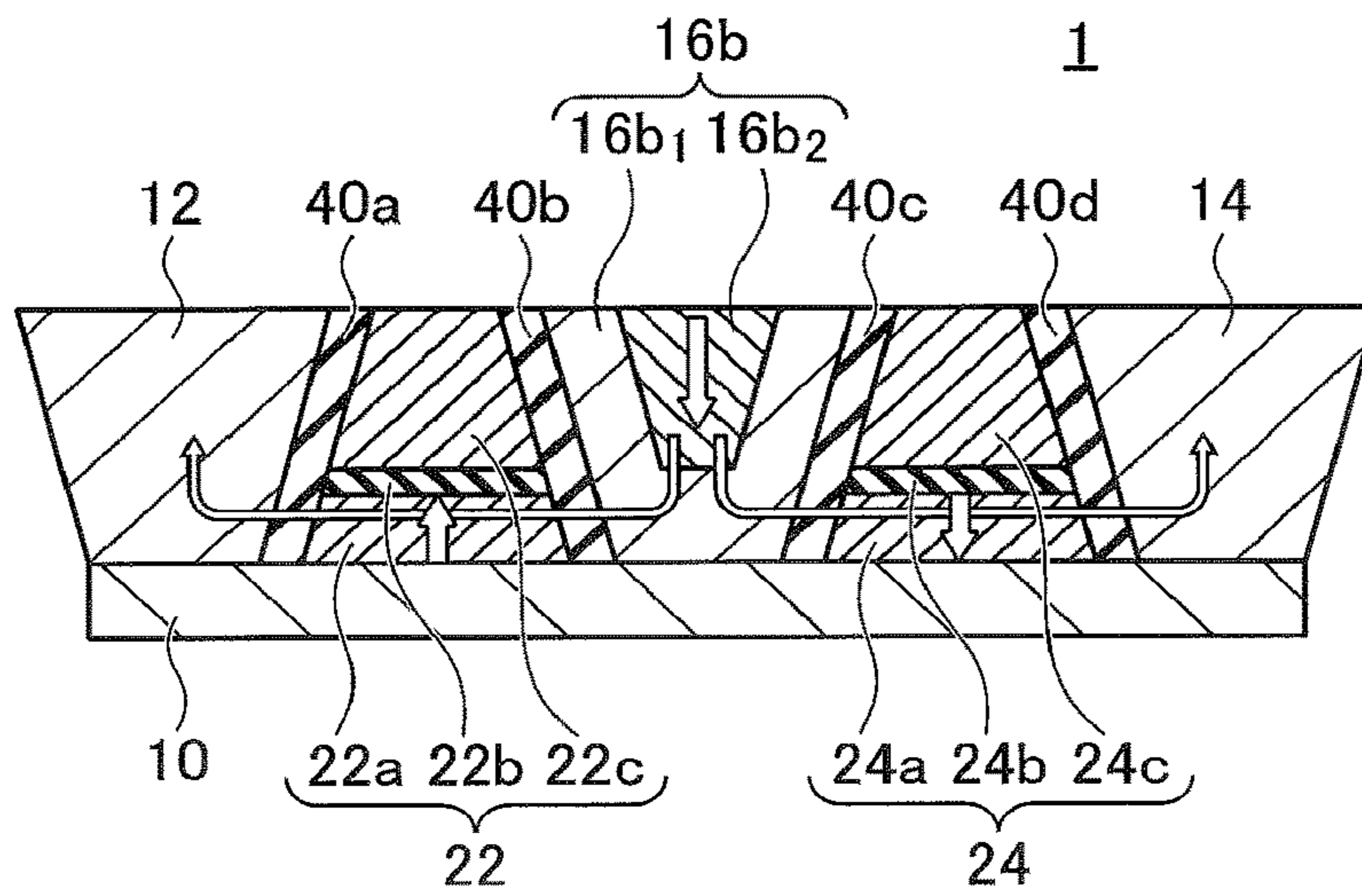


FIG. 37

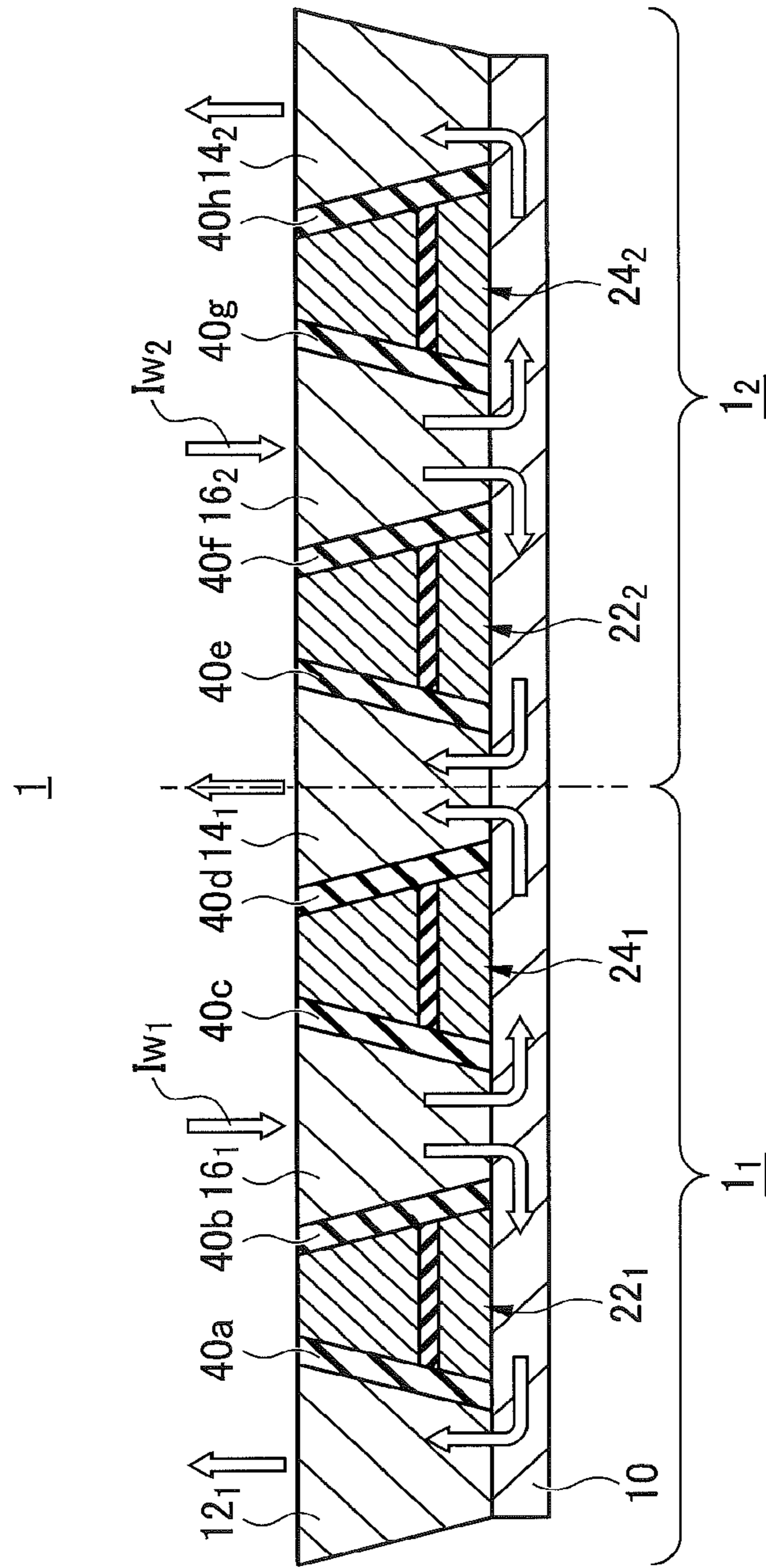


FIG. 38

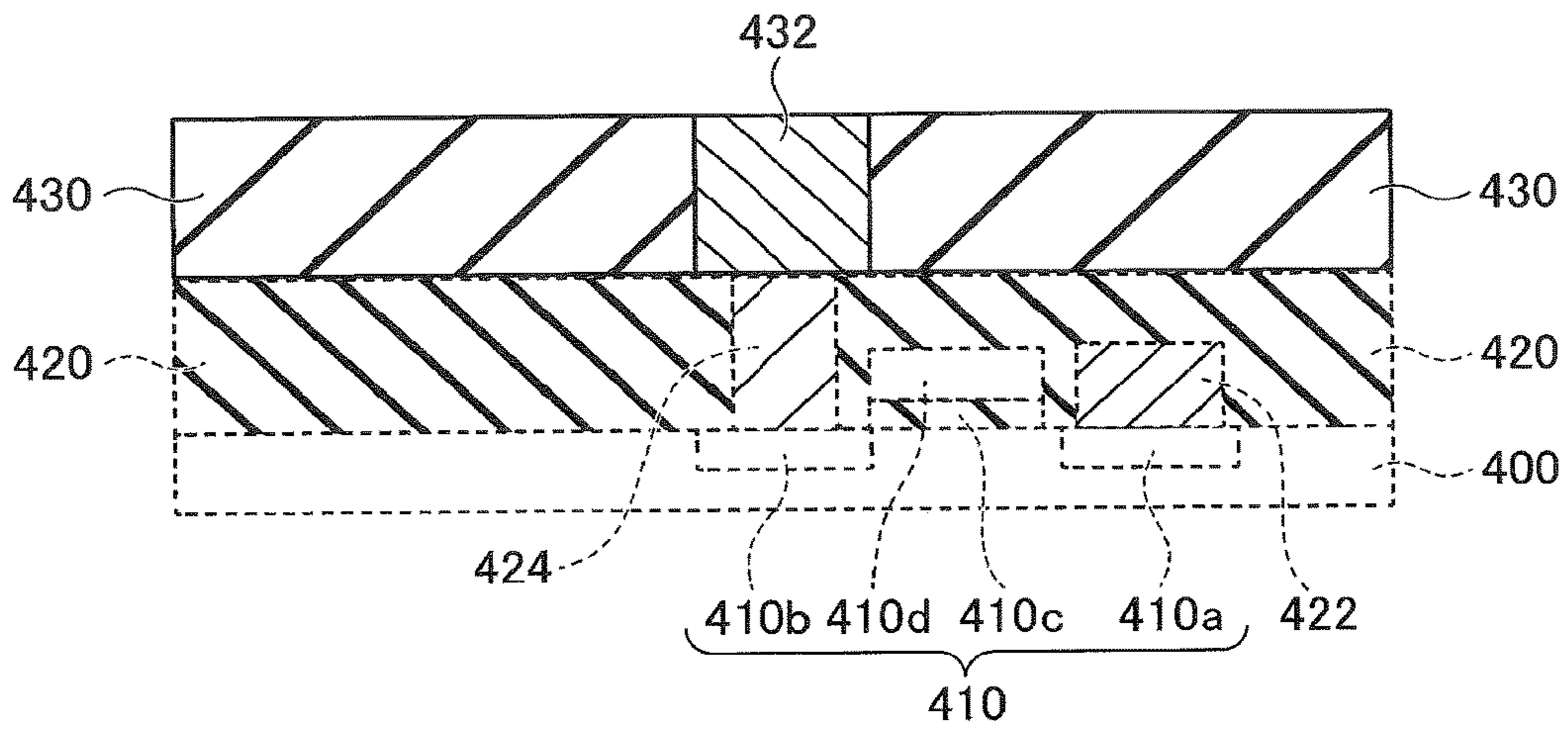


FIG. 39

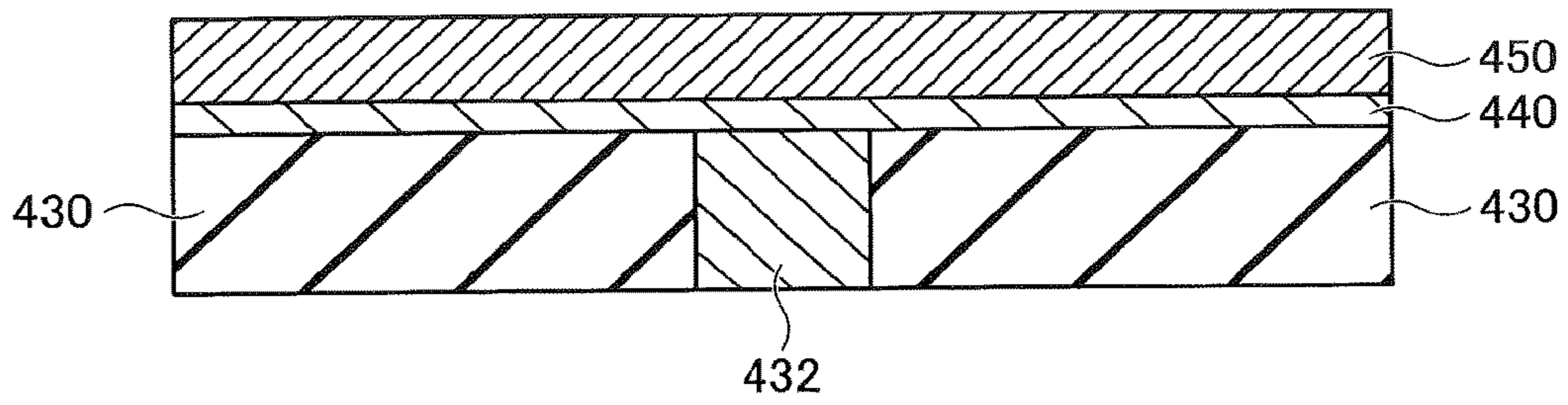


FIG. 40

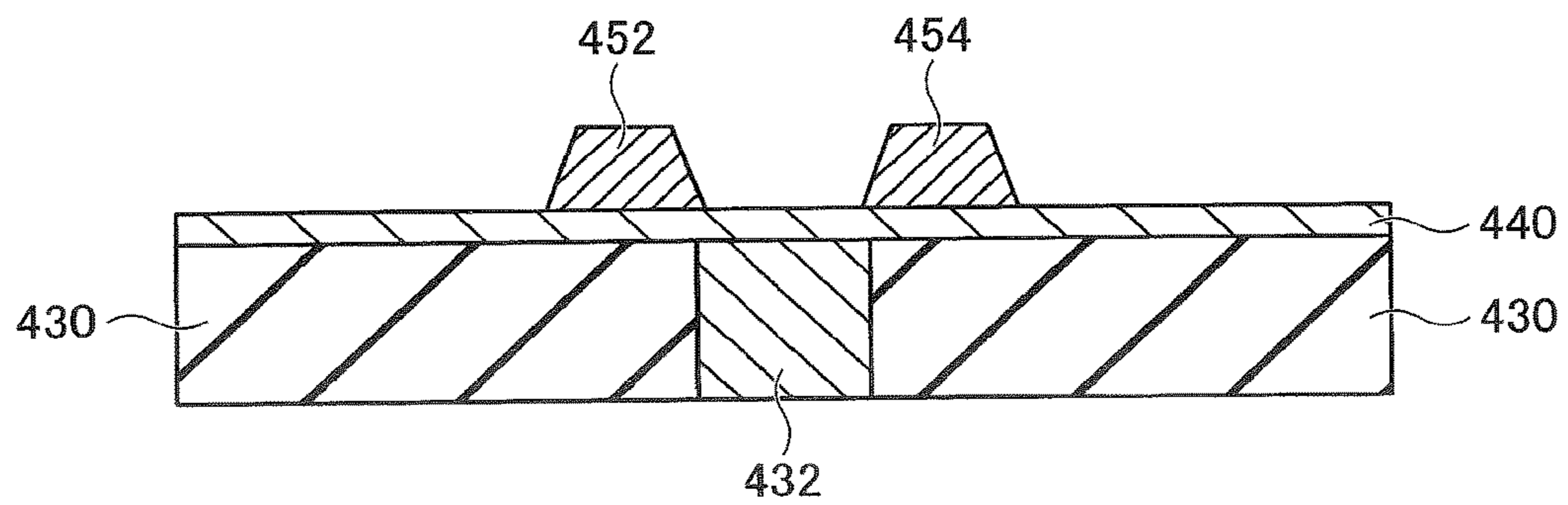


FIG. 41

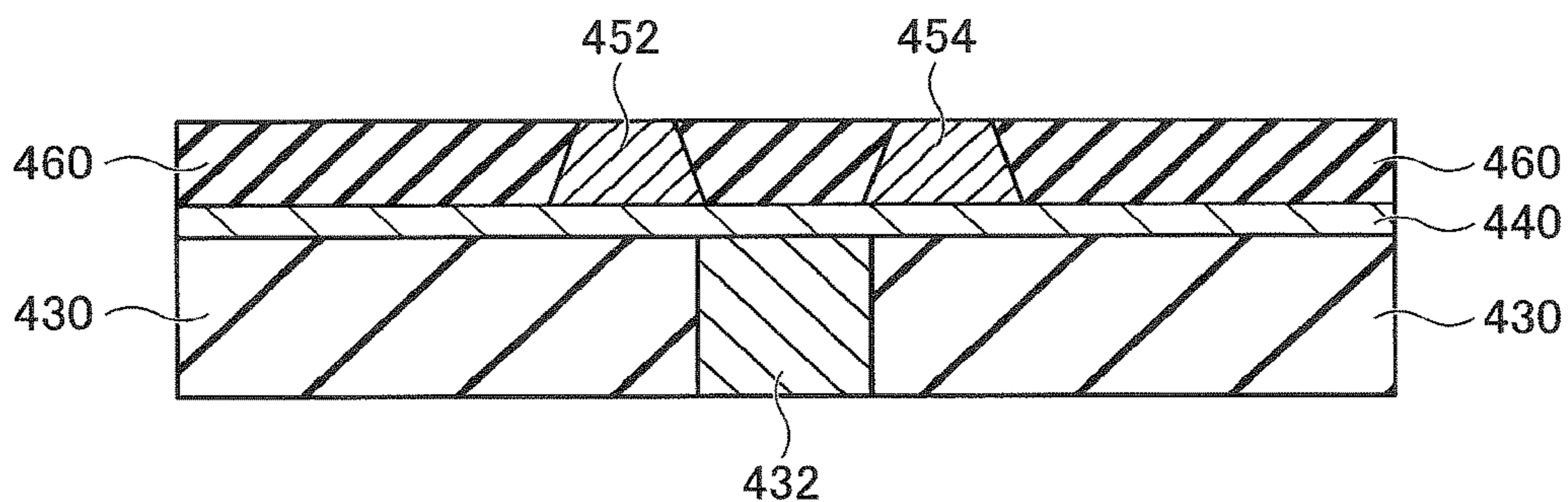


FIG. 42

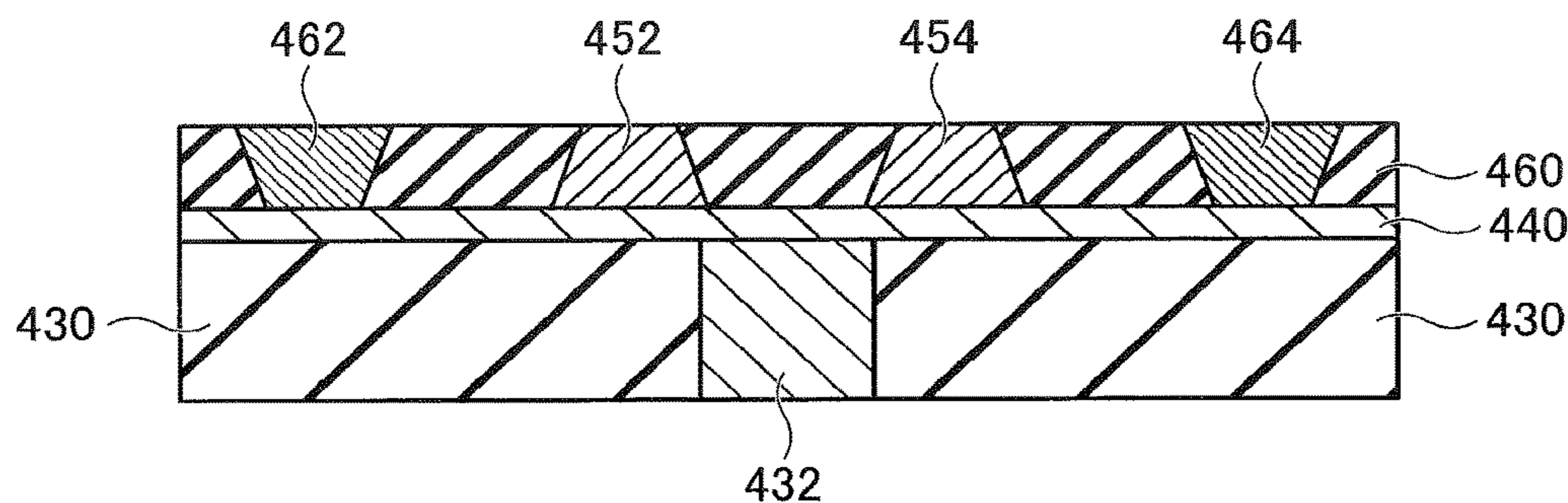


FIG. 43

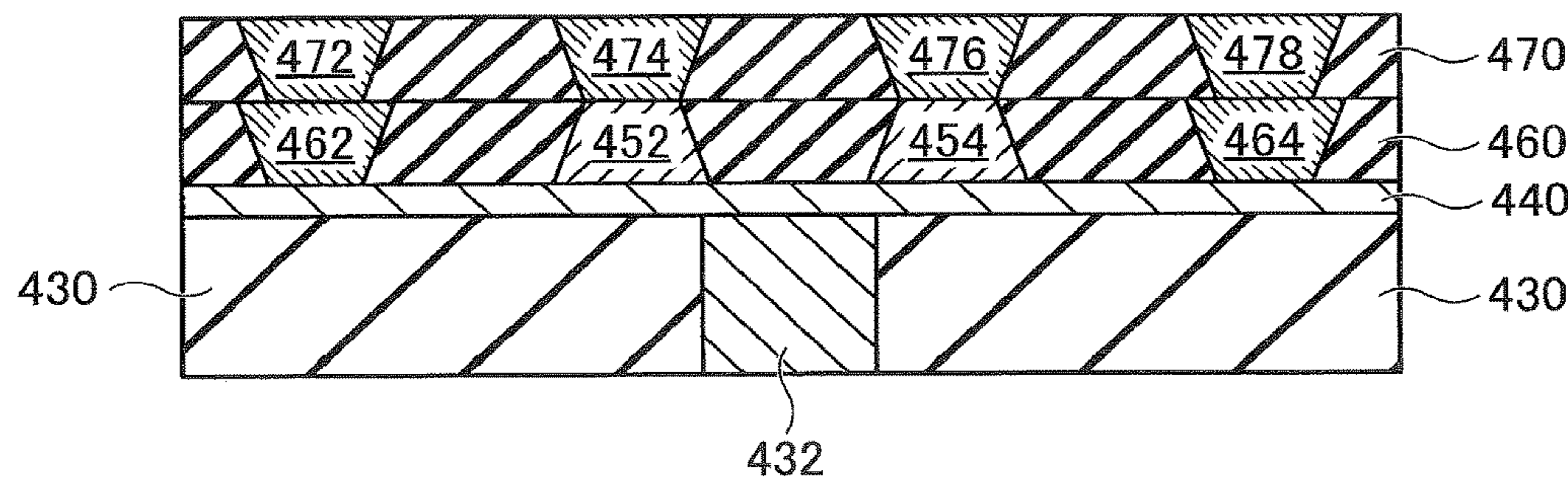


FIG. 44

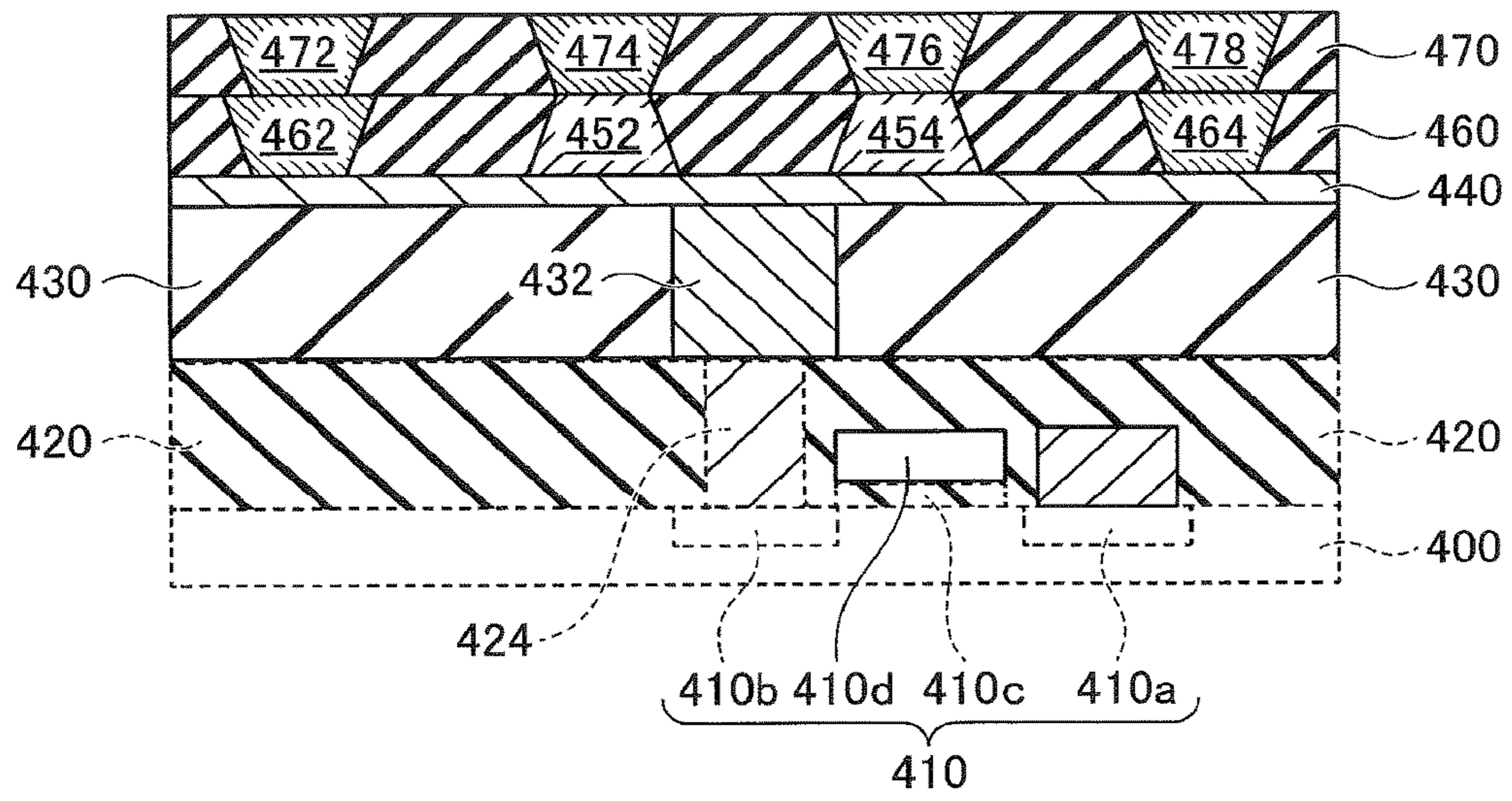


FIG. 45

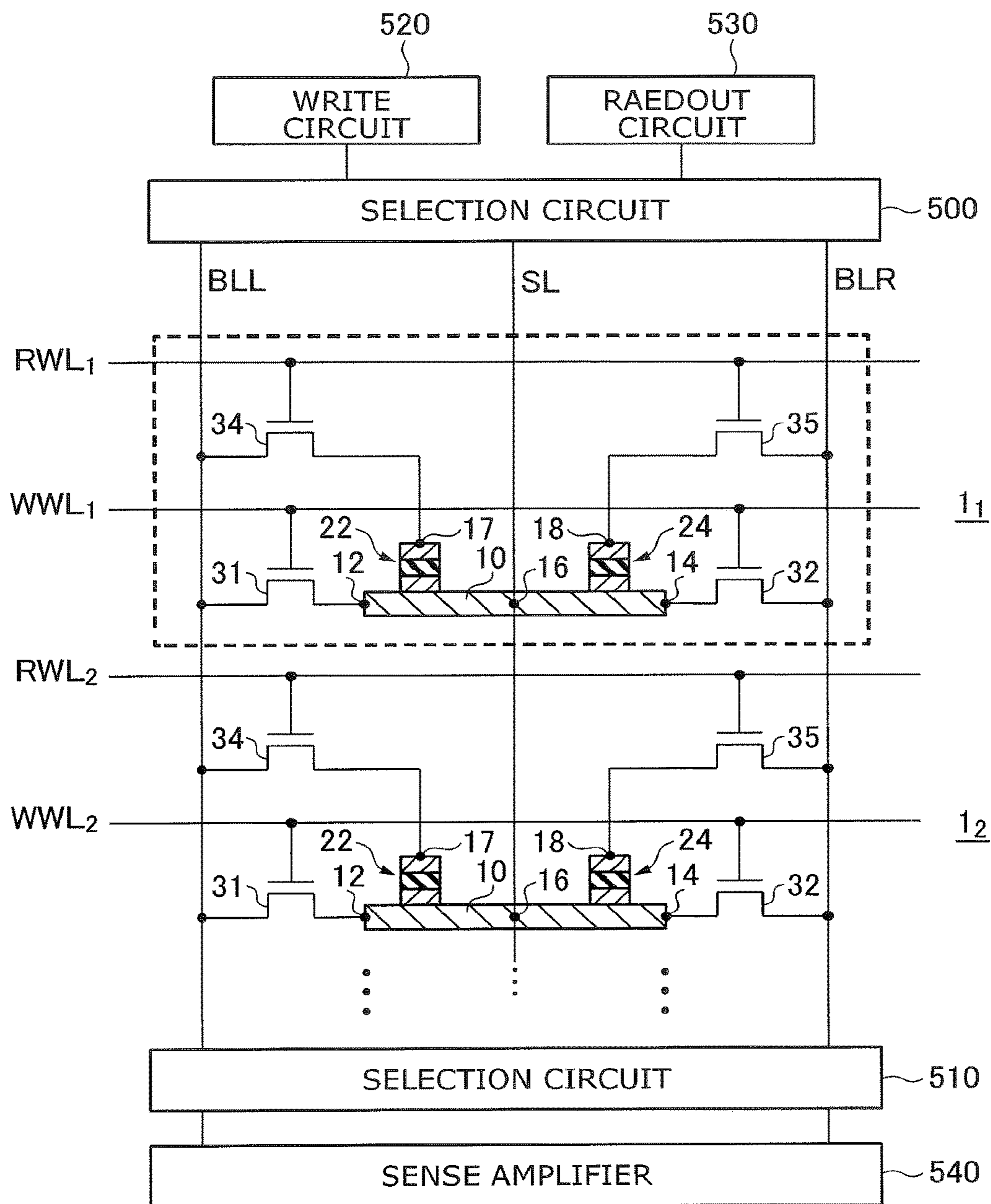


FIG. 46

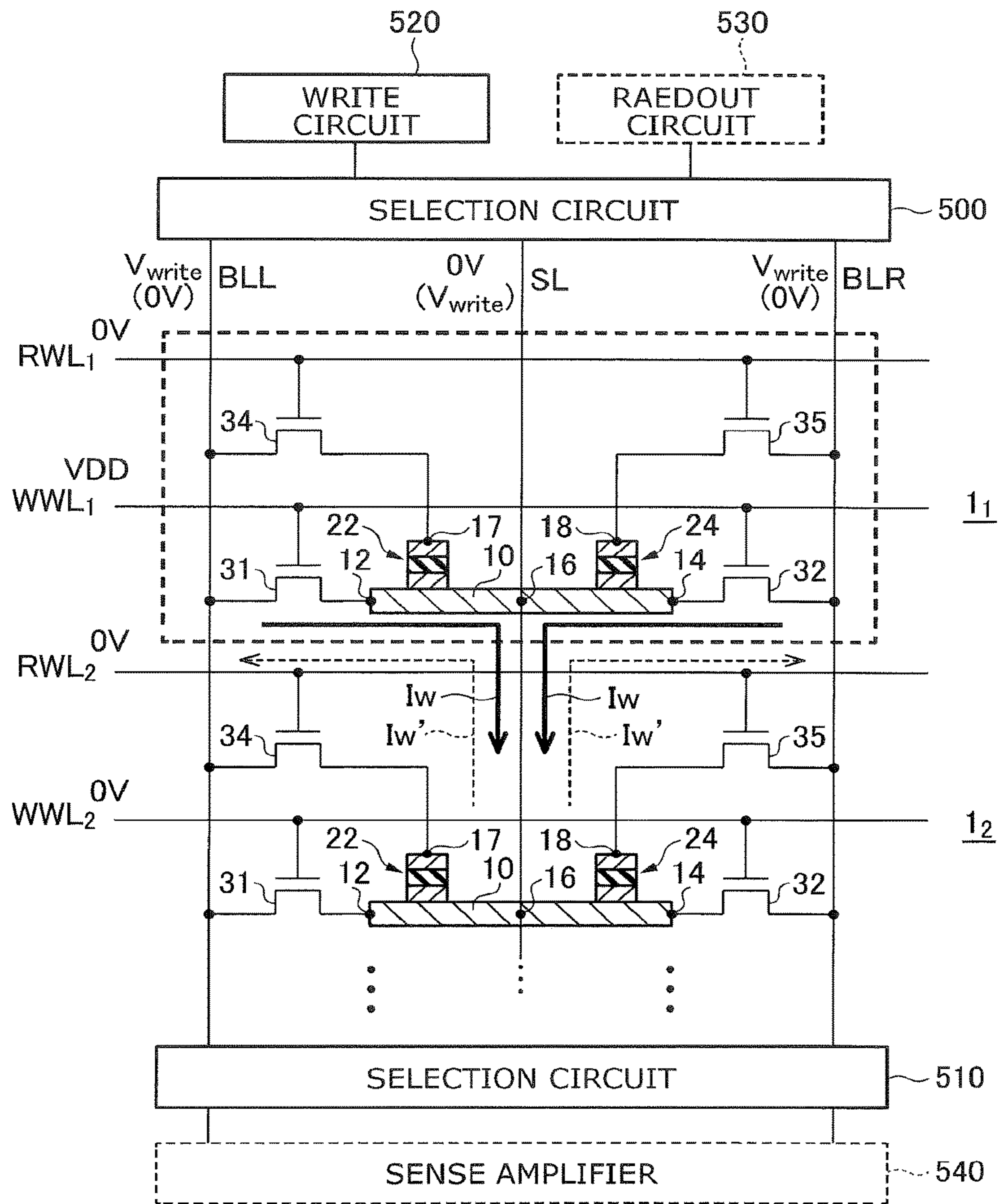


FIG. 47



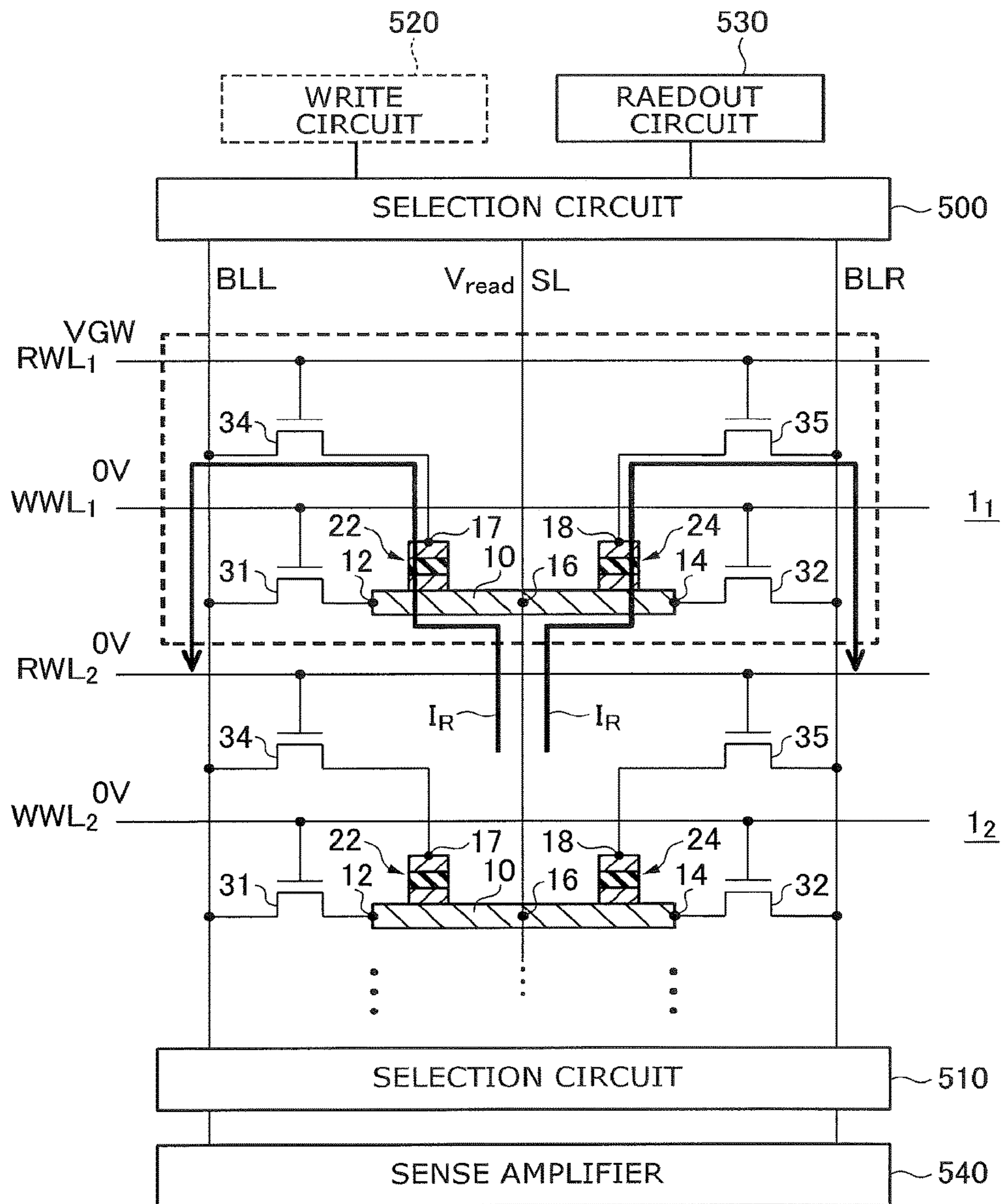


FIG. 48

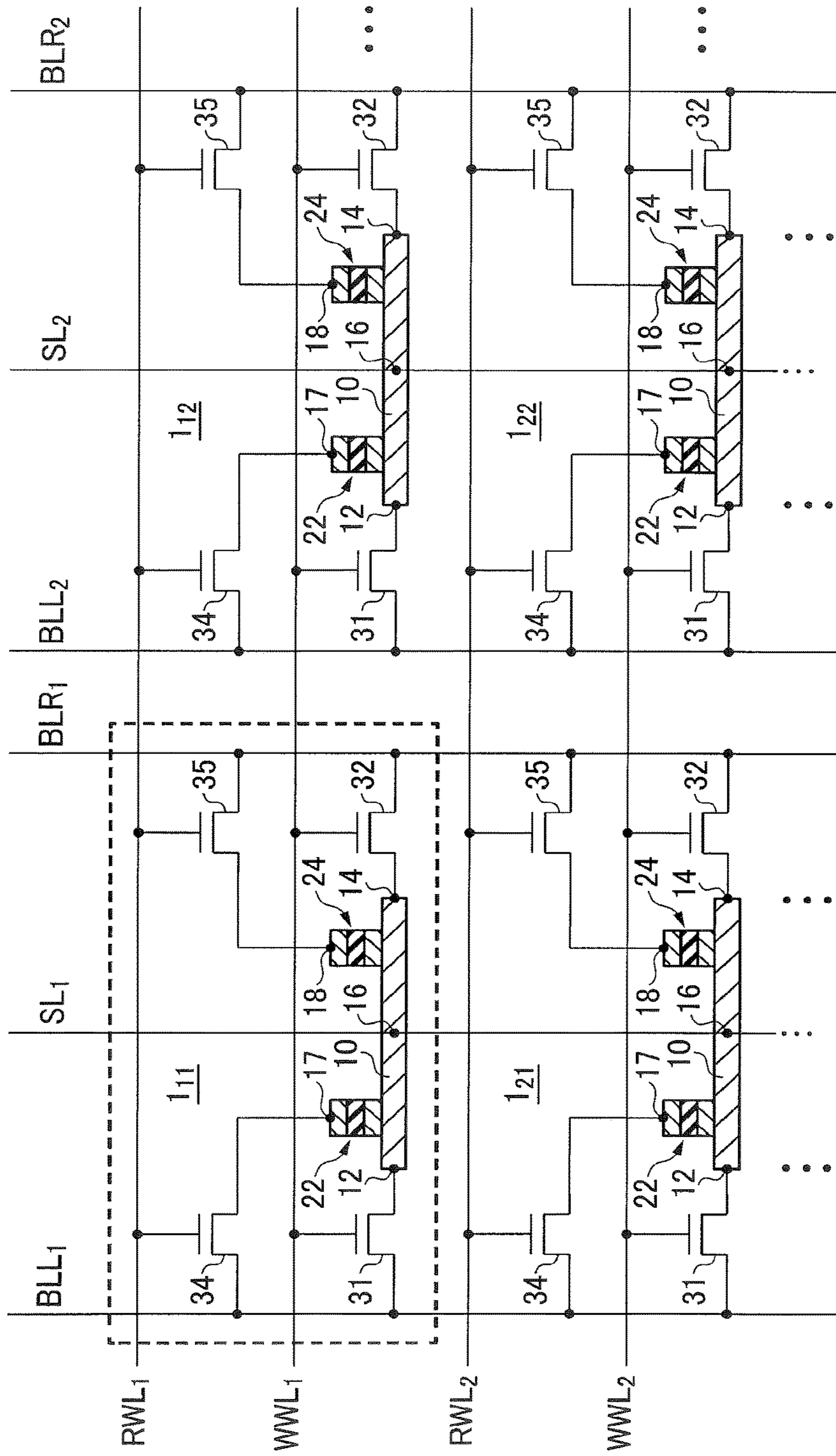


FIG. 49

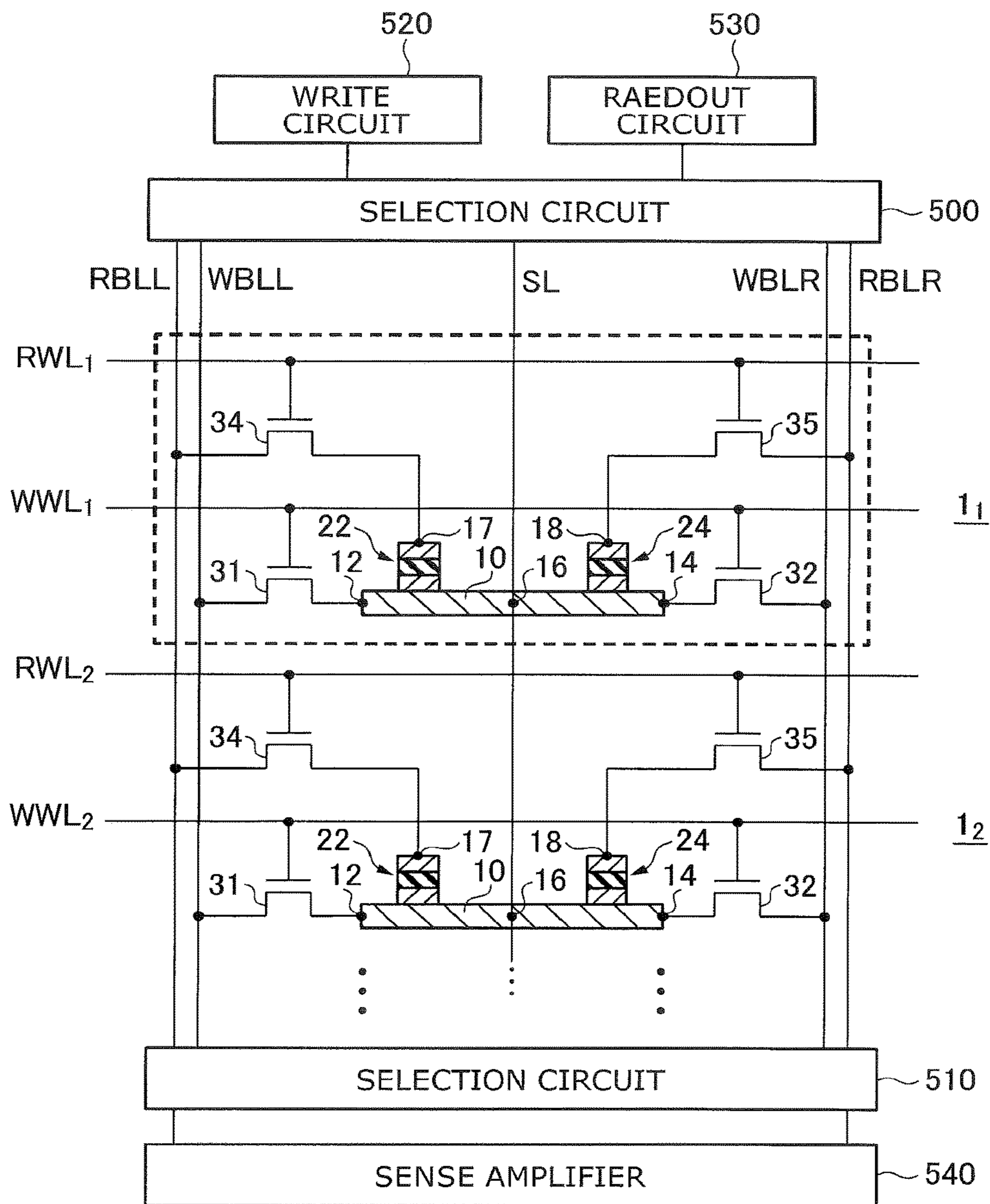


FIG. 50

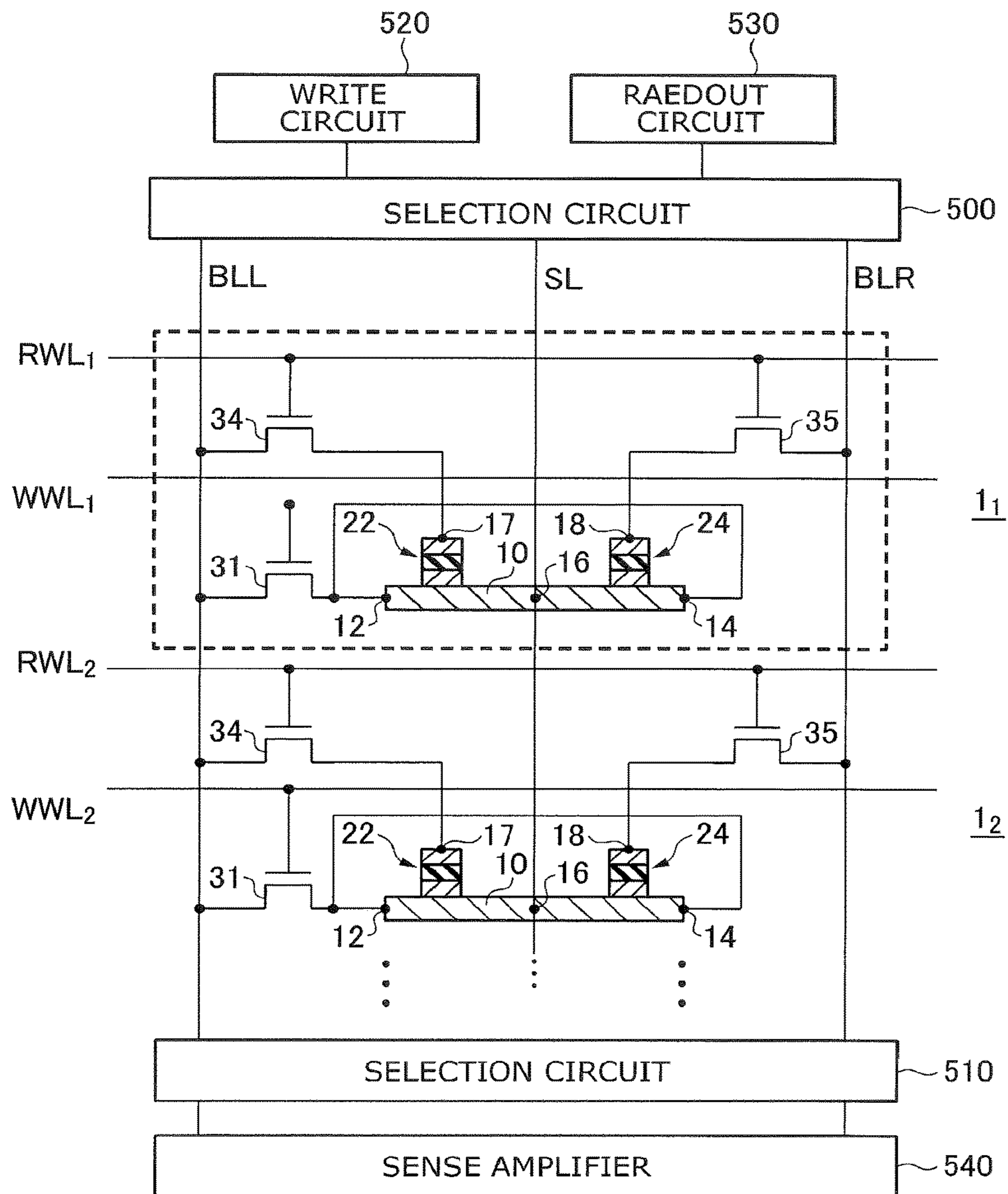


FIG. 51

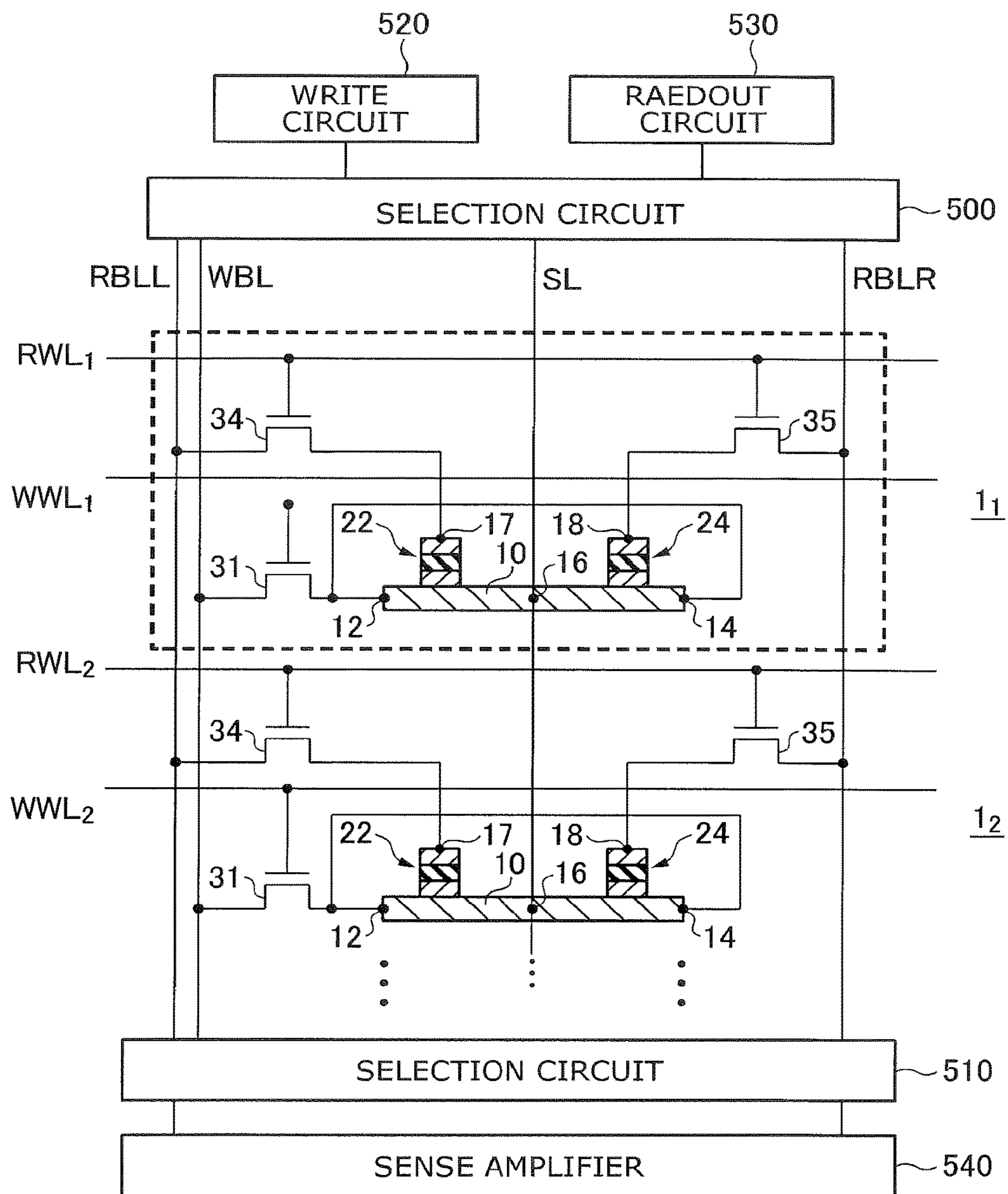


FIG. 52

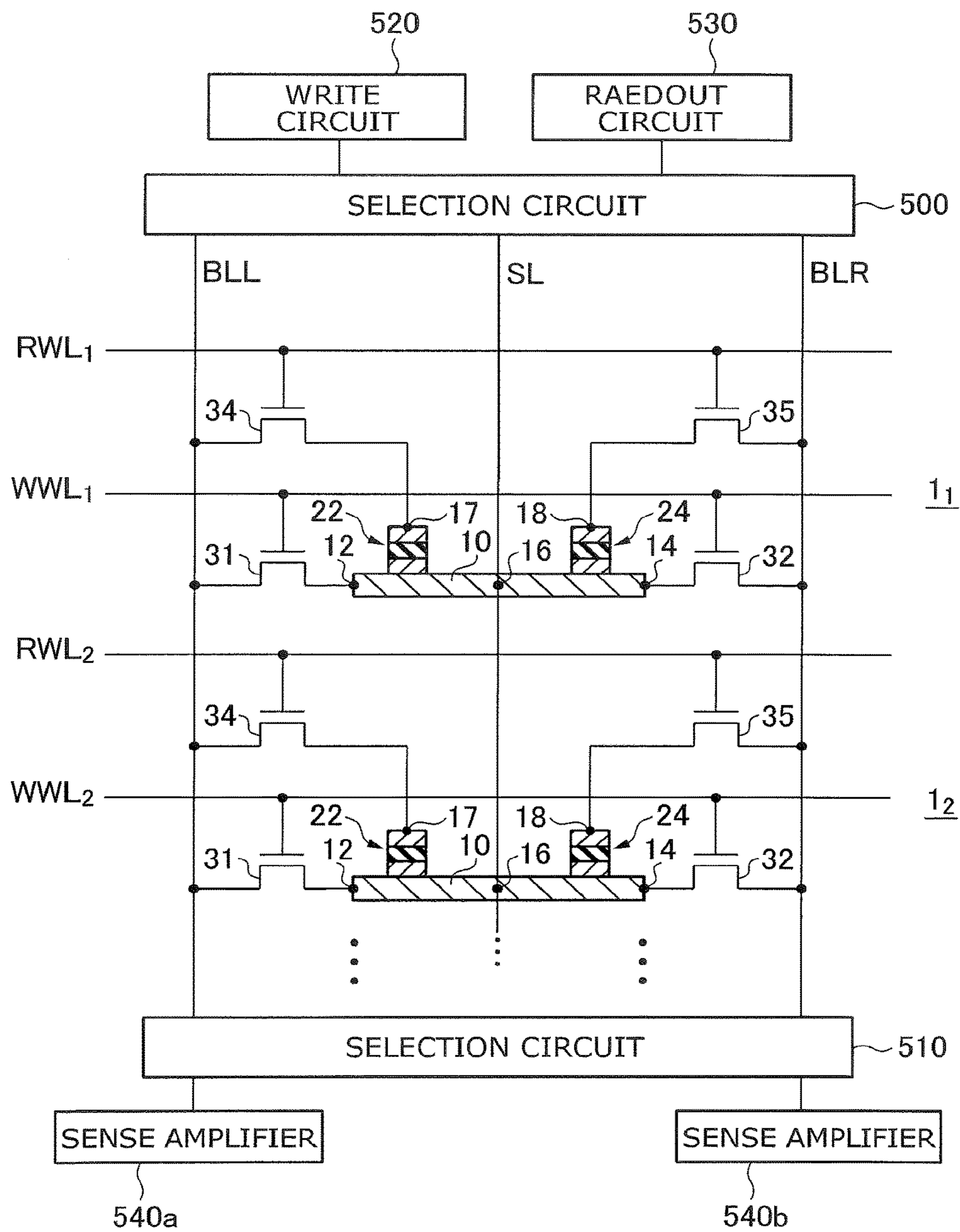


FIG. 53

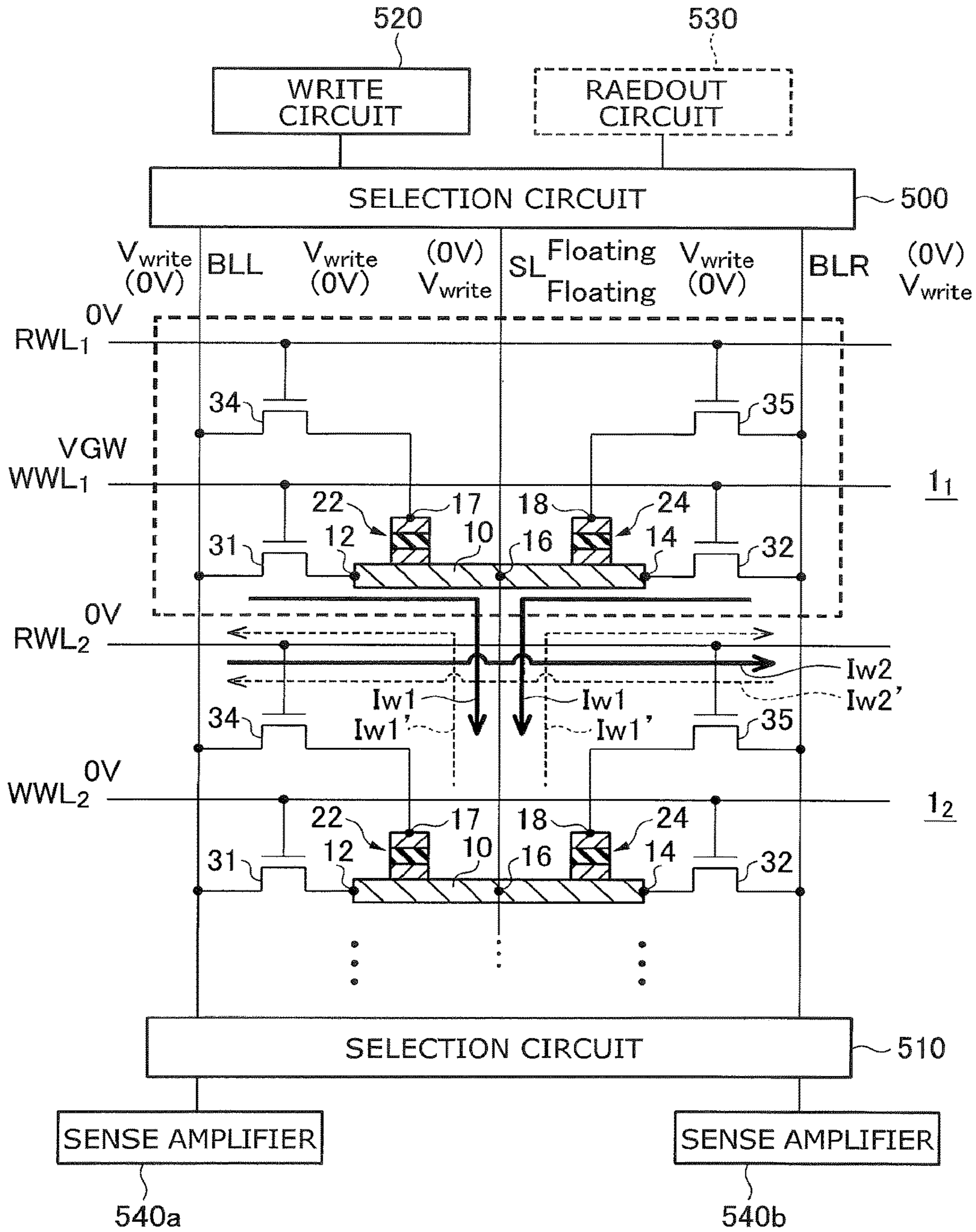


FIG. 54

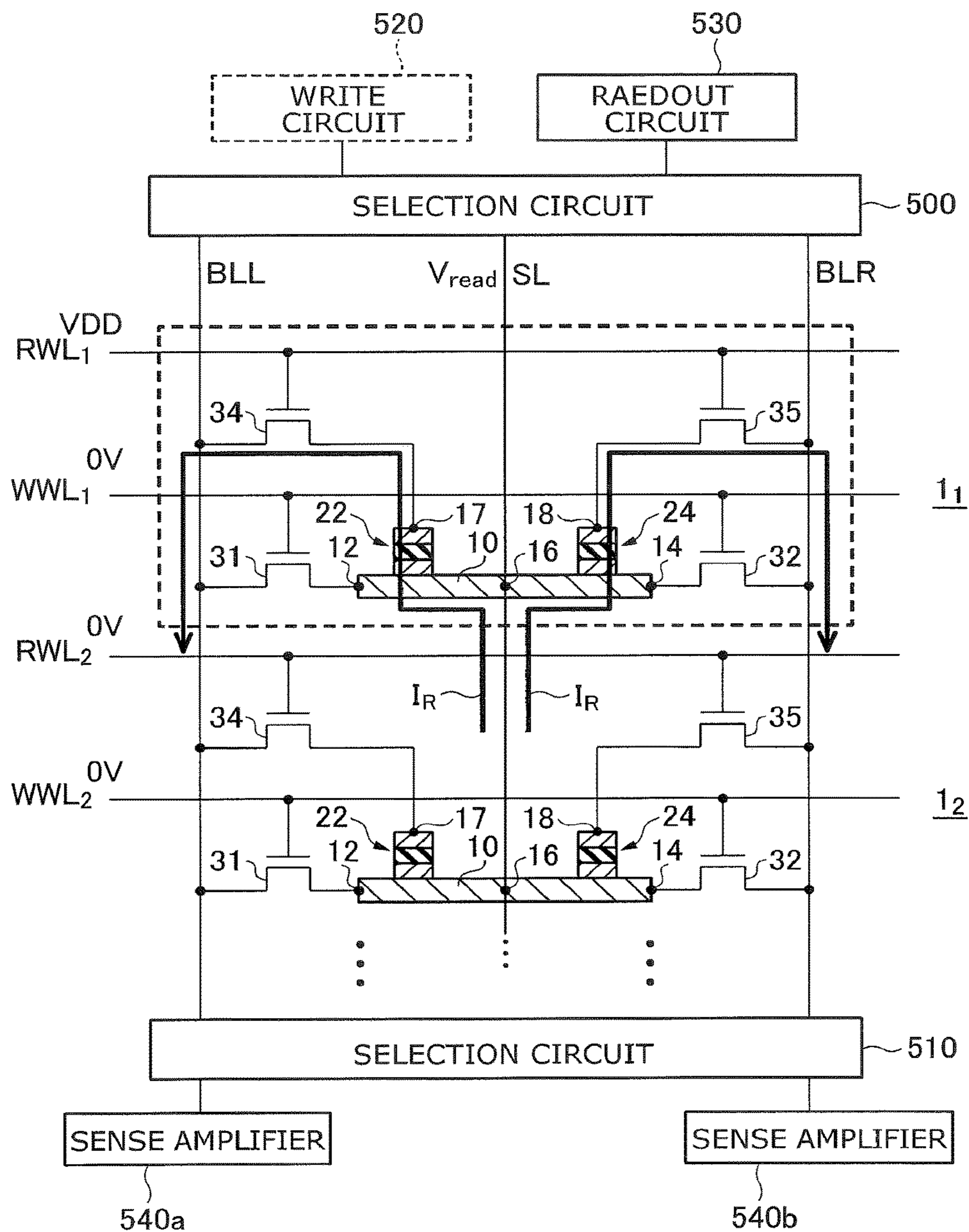


FIG. 55



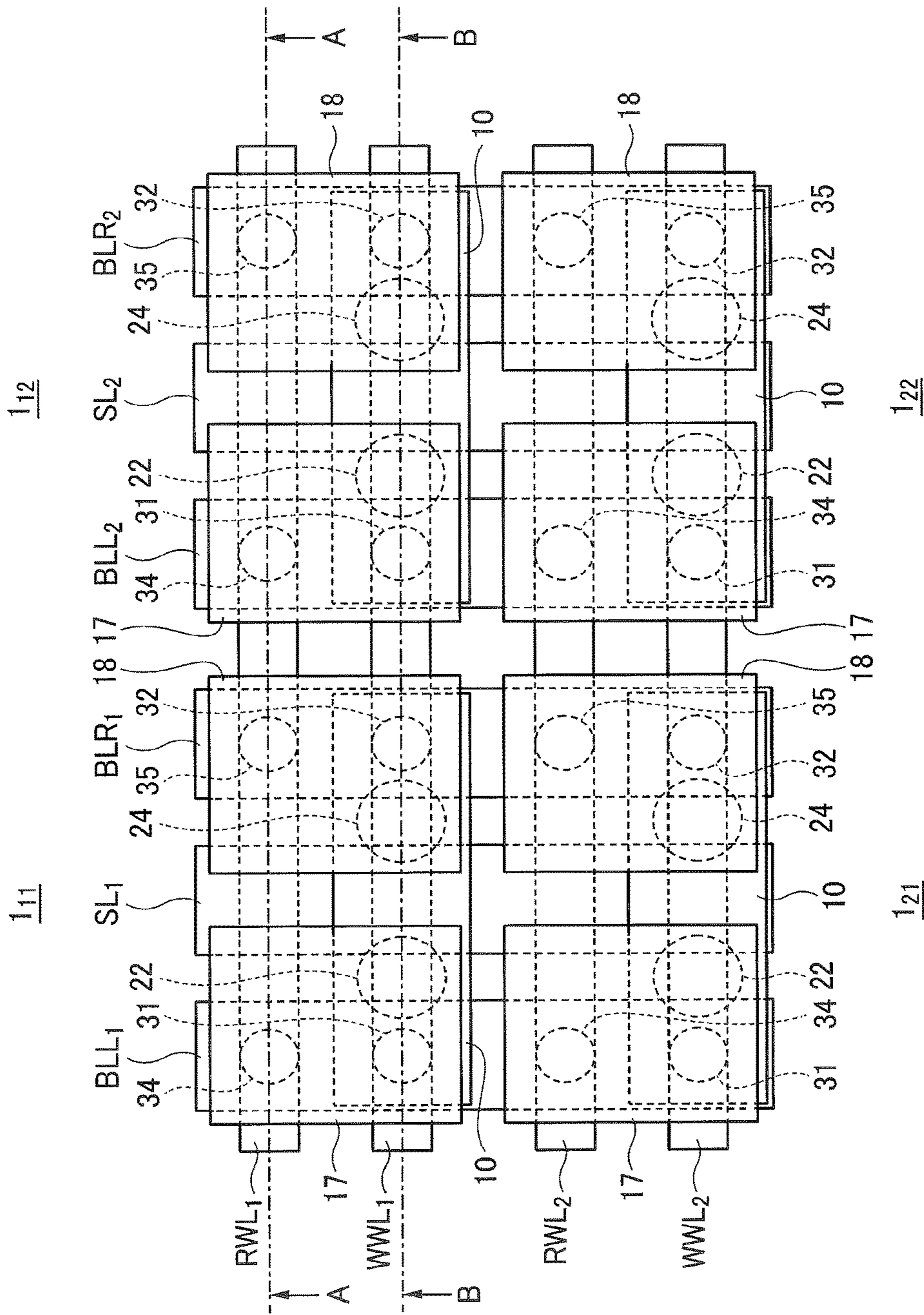


FIG. 56

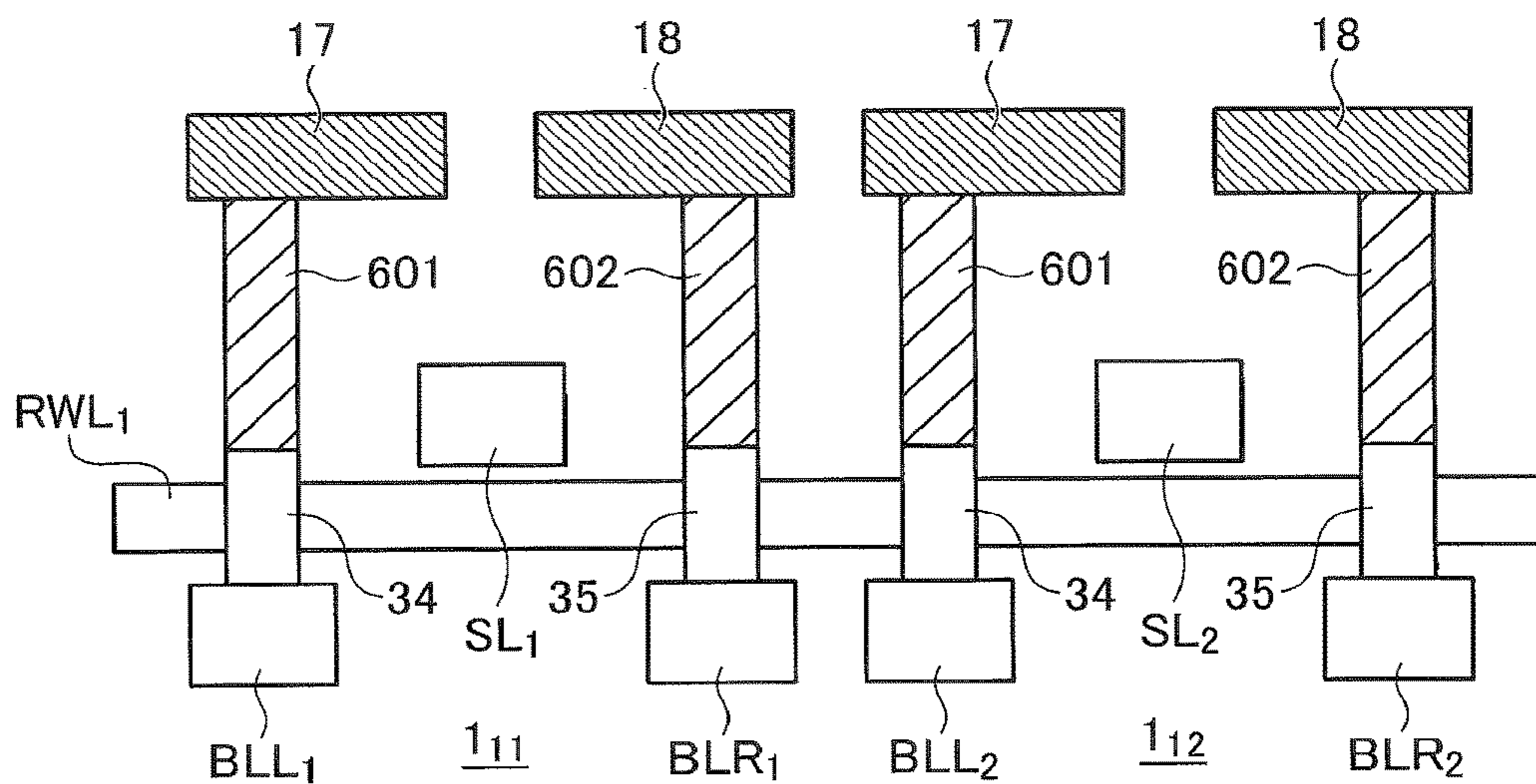


FIG. 57

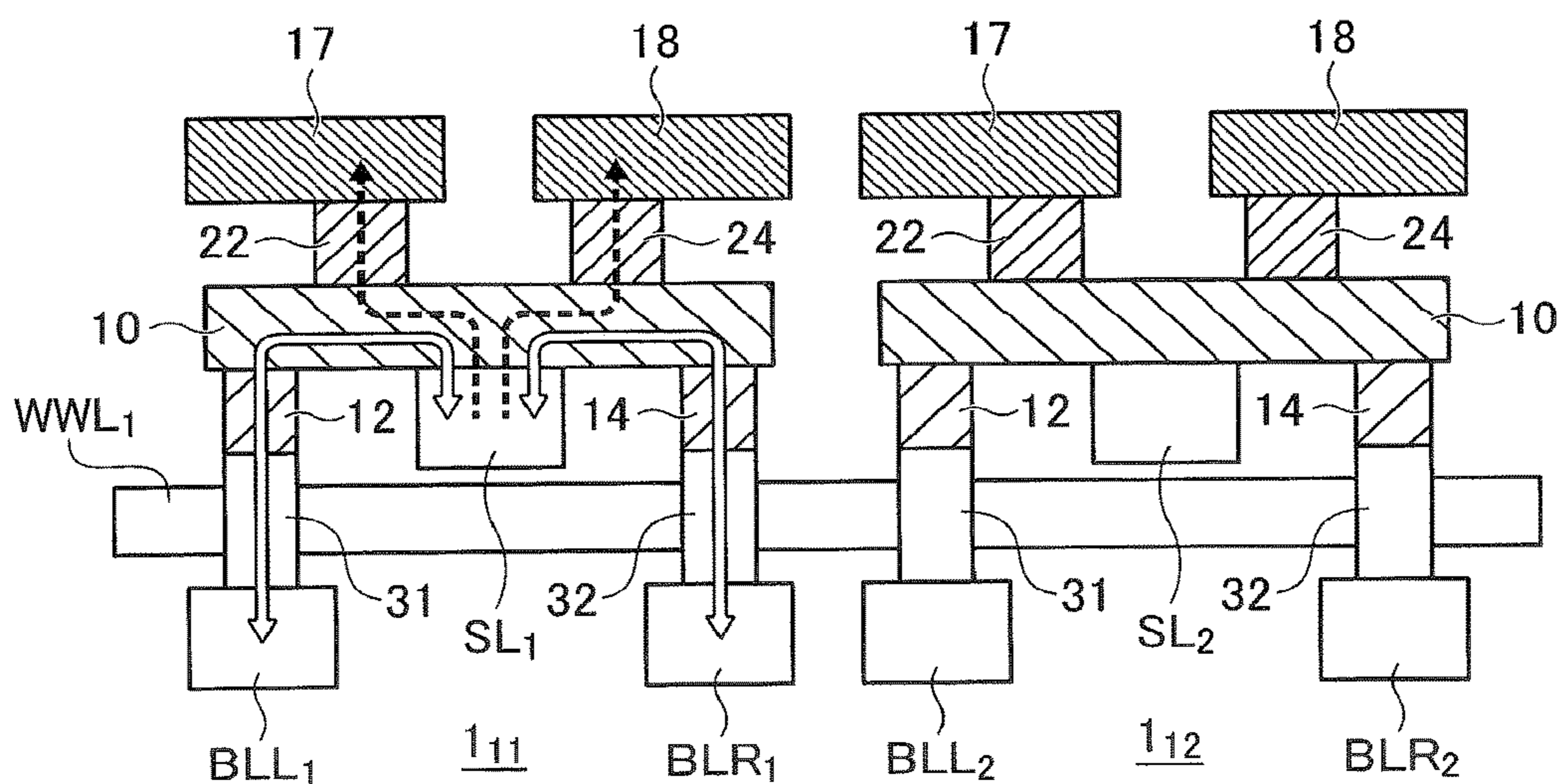


FIG. 58

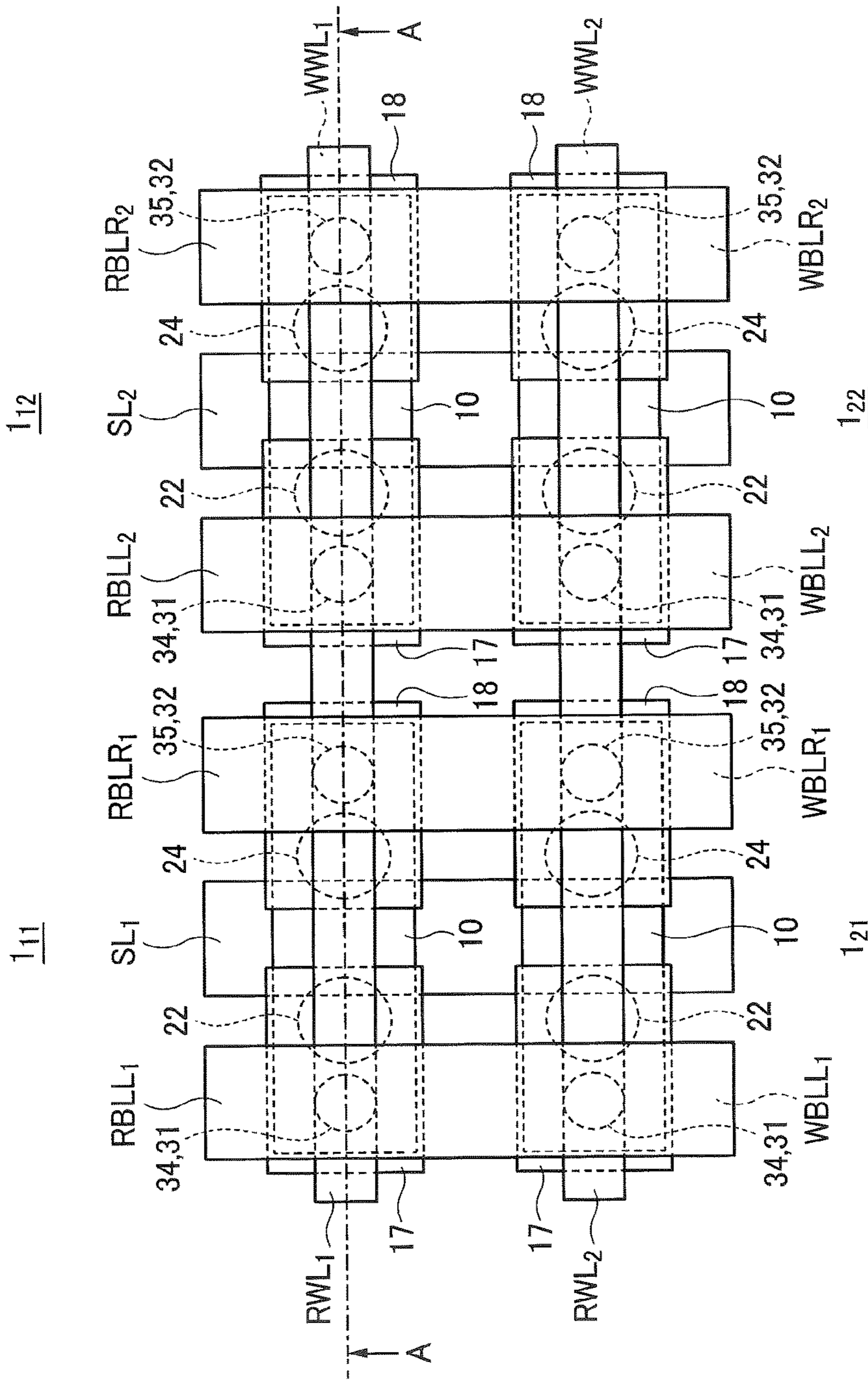


FIG. 59

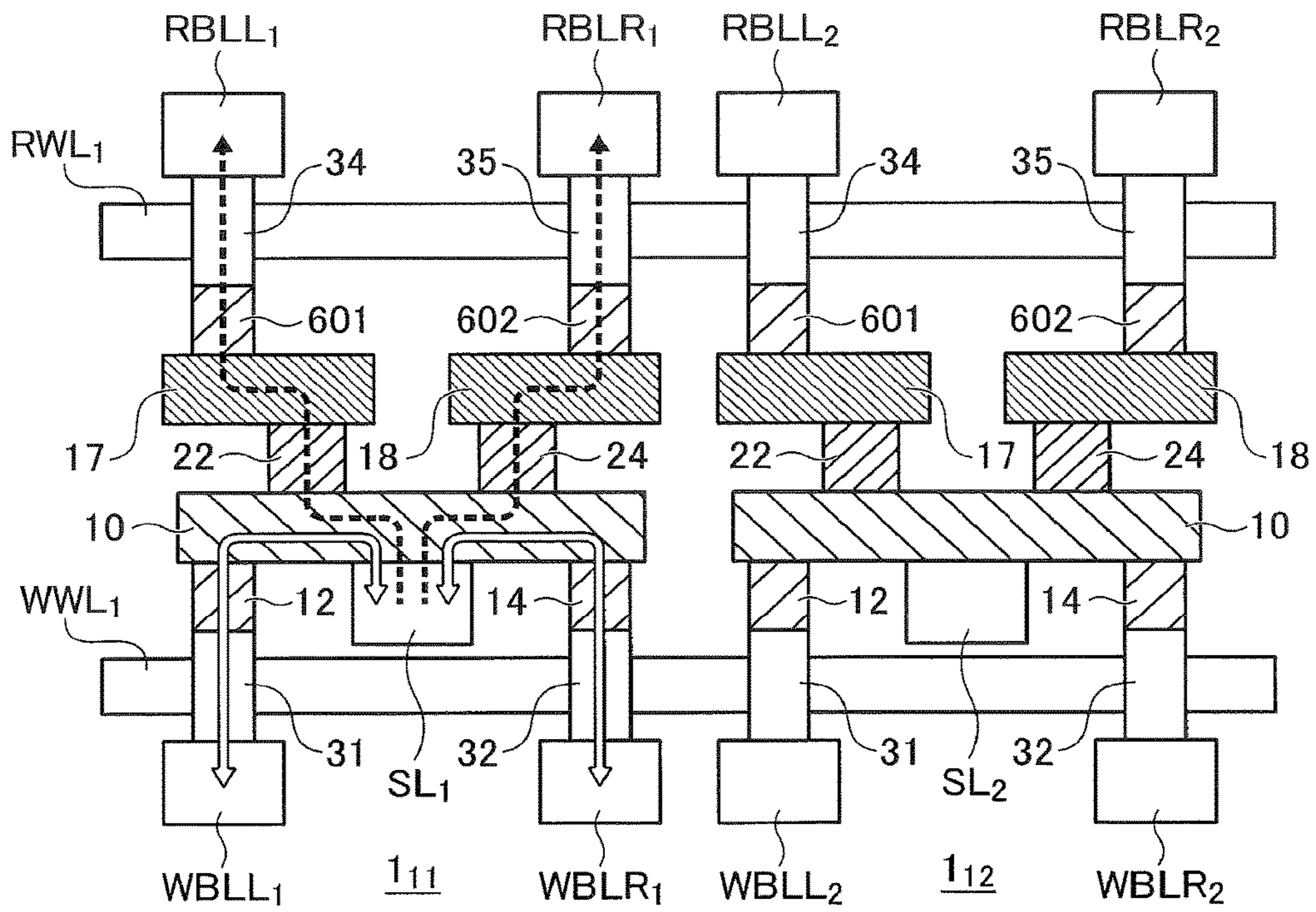


FIG. 60

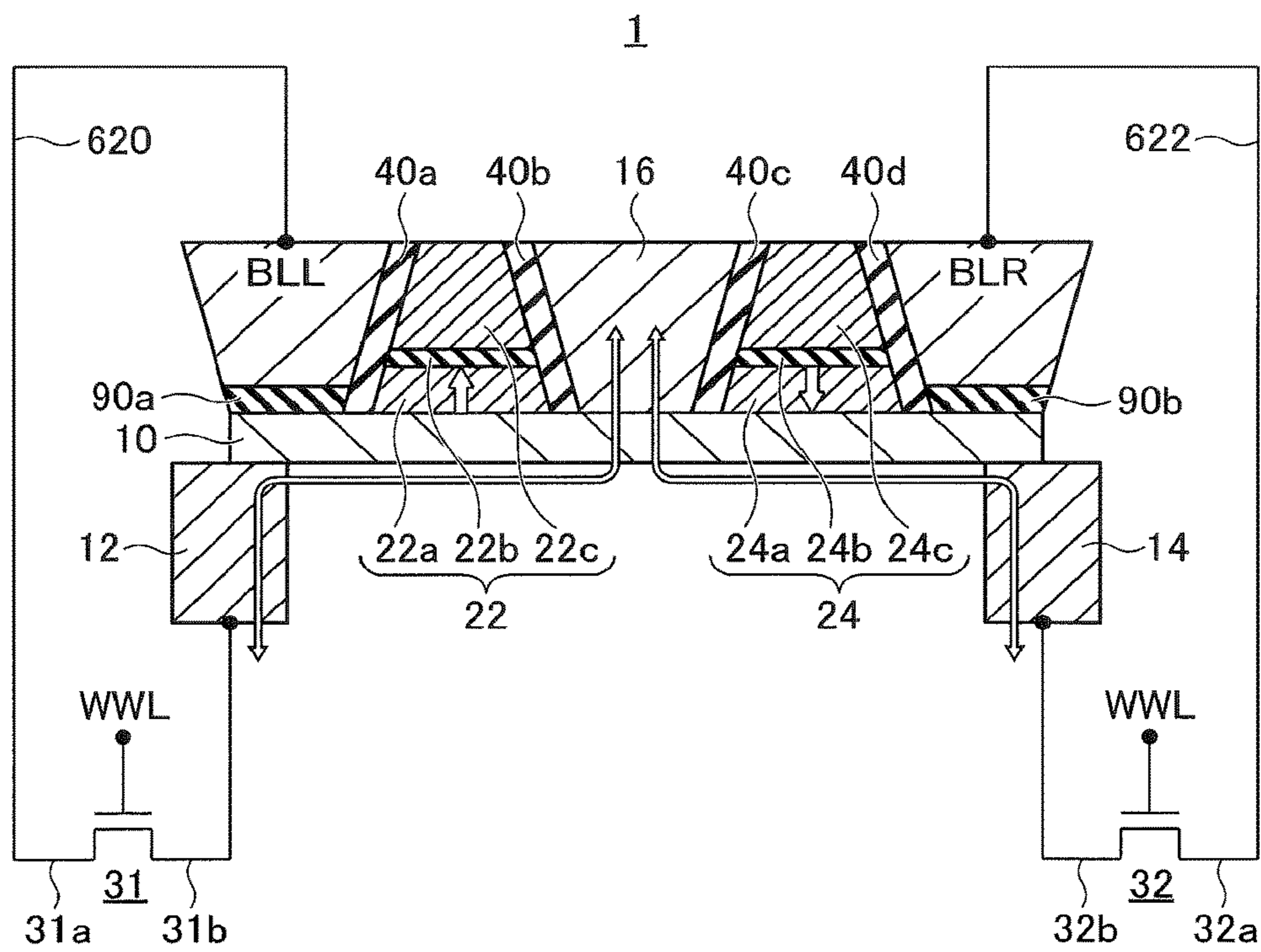


FIG. 61

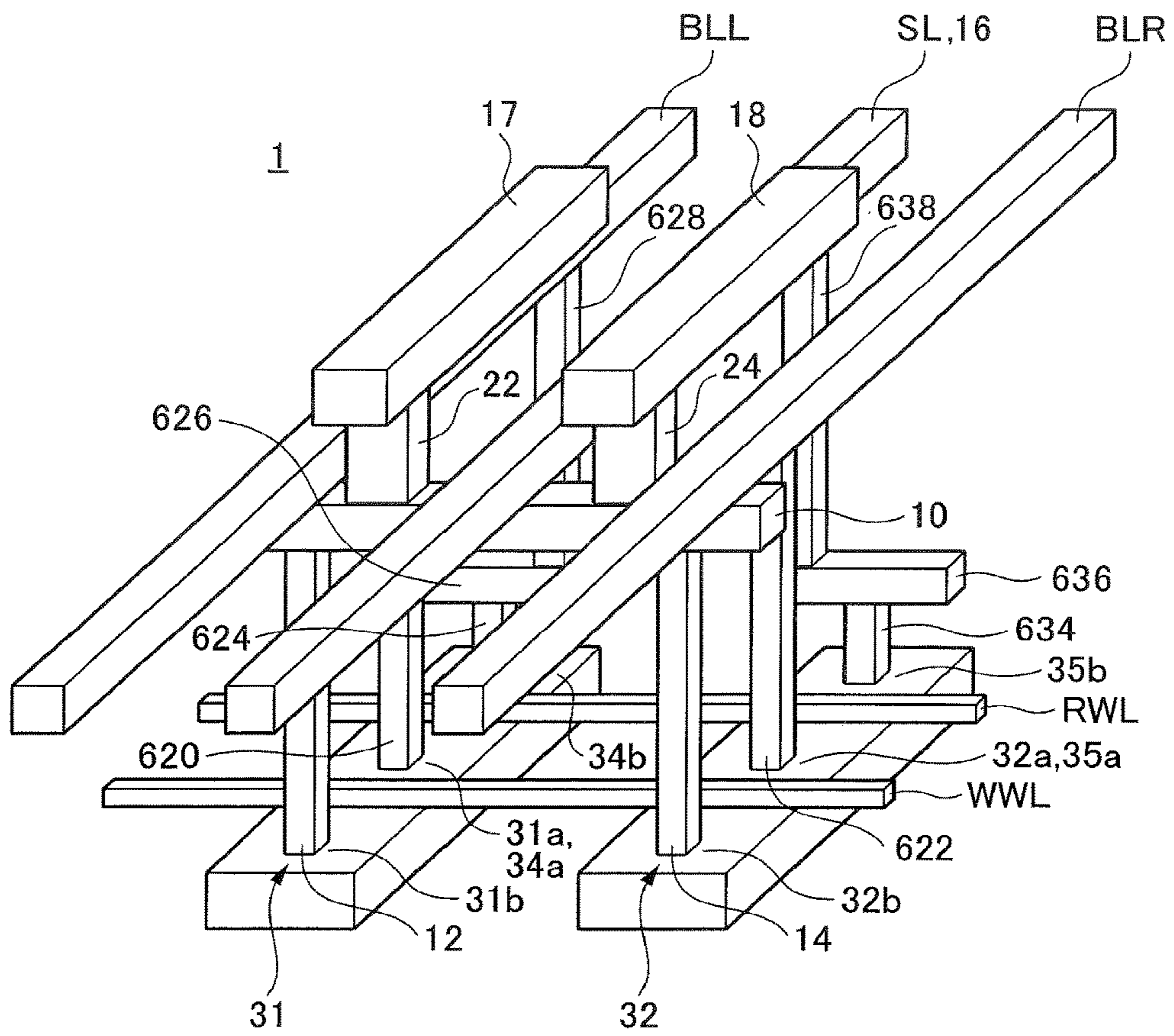


FIG. 62

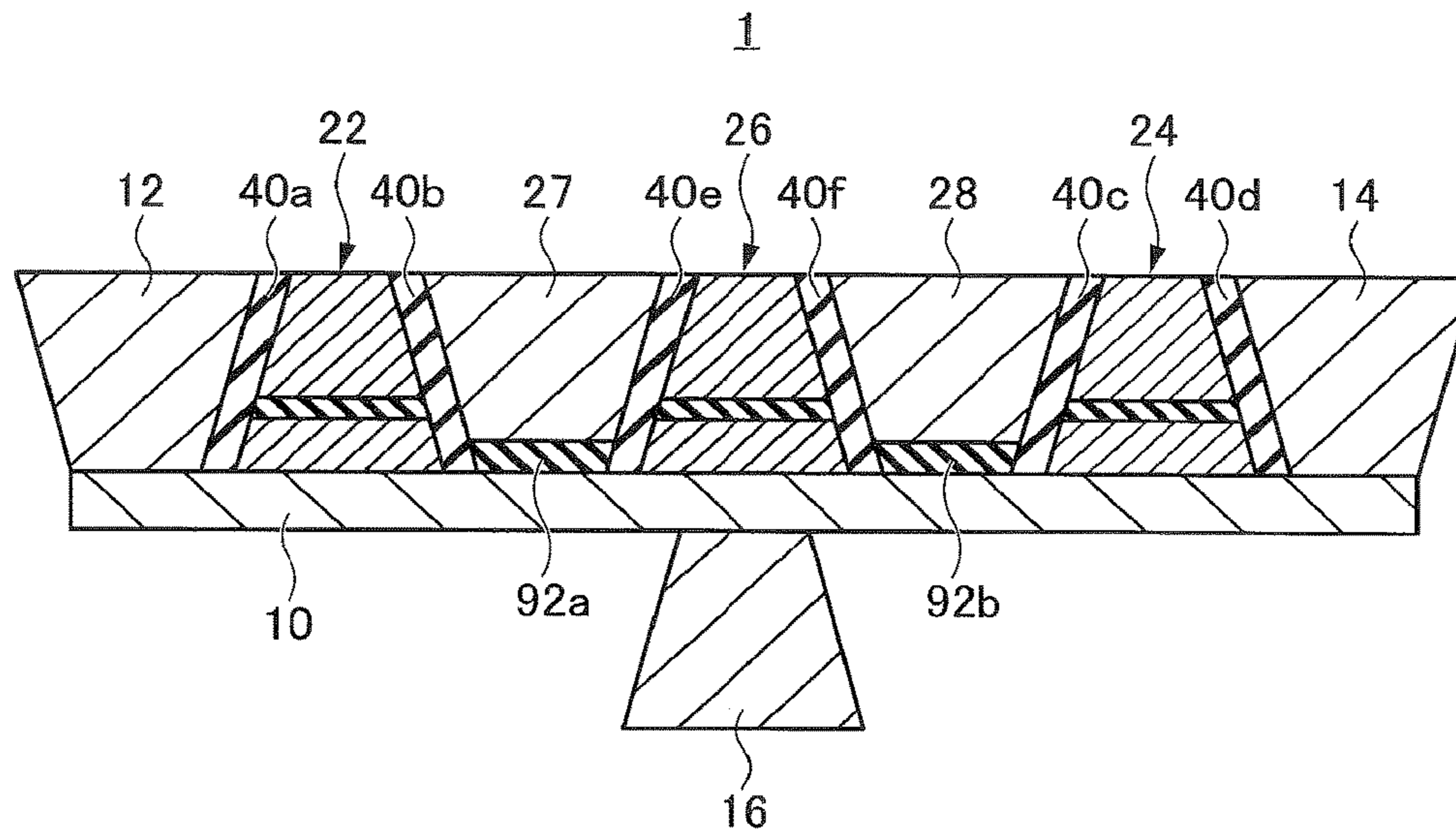


FIG. 63

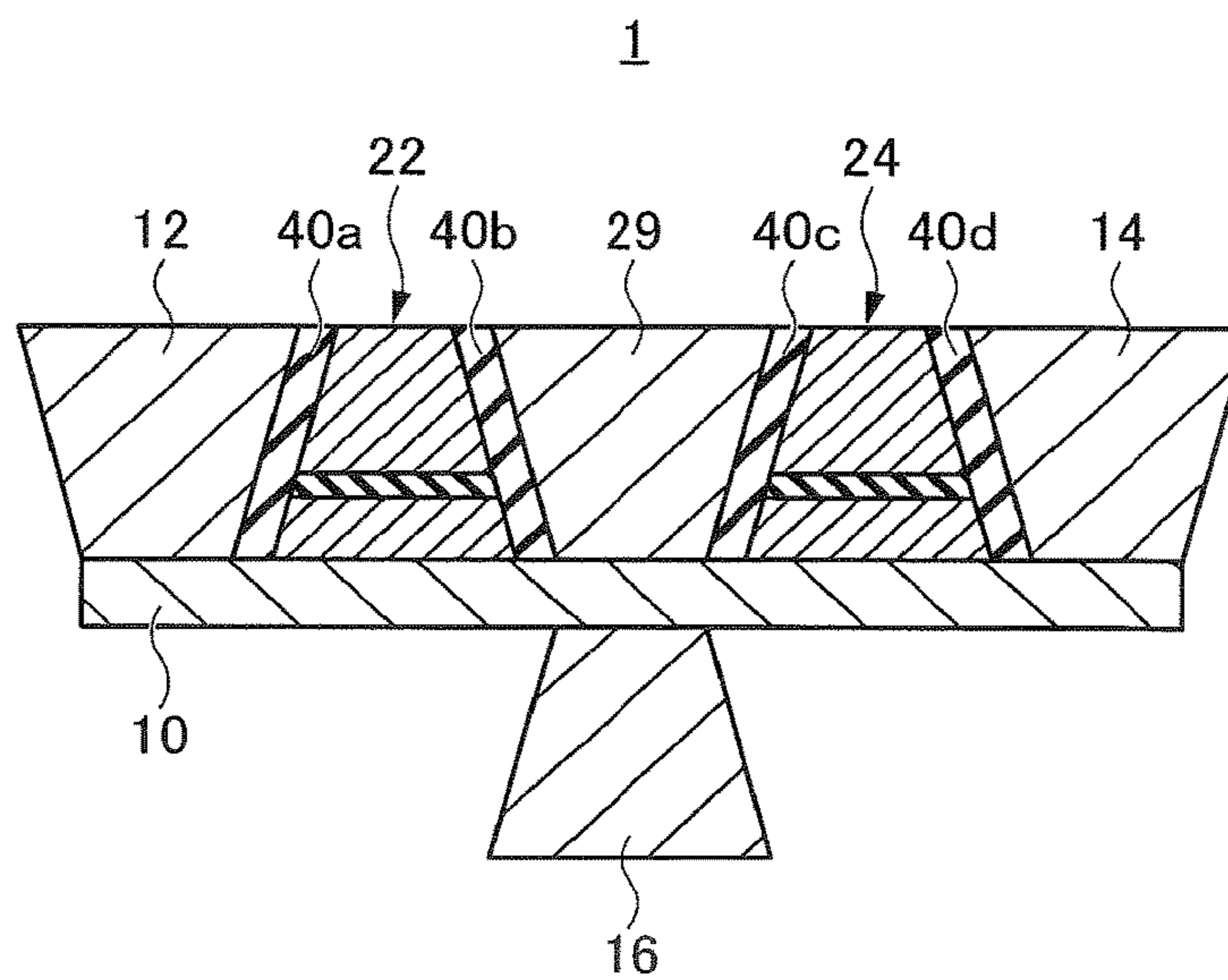


FIG. 64

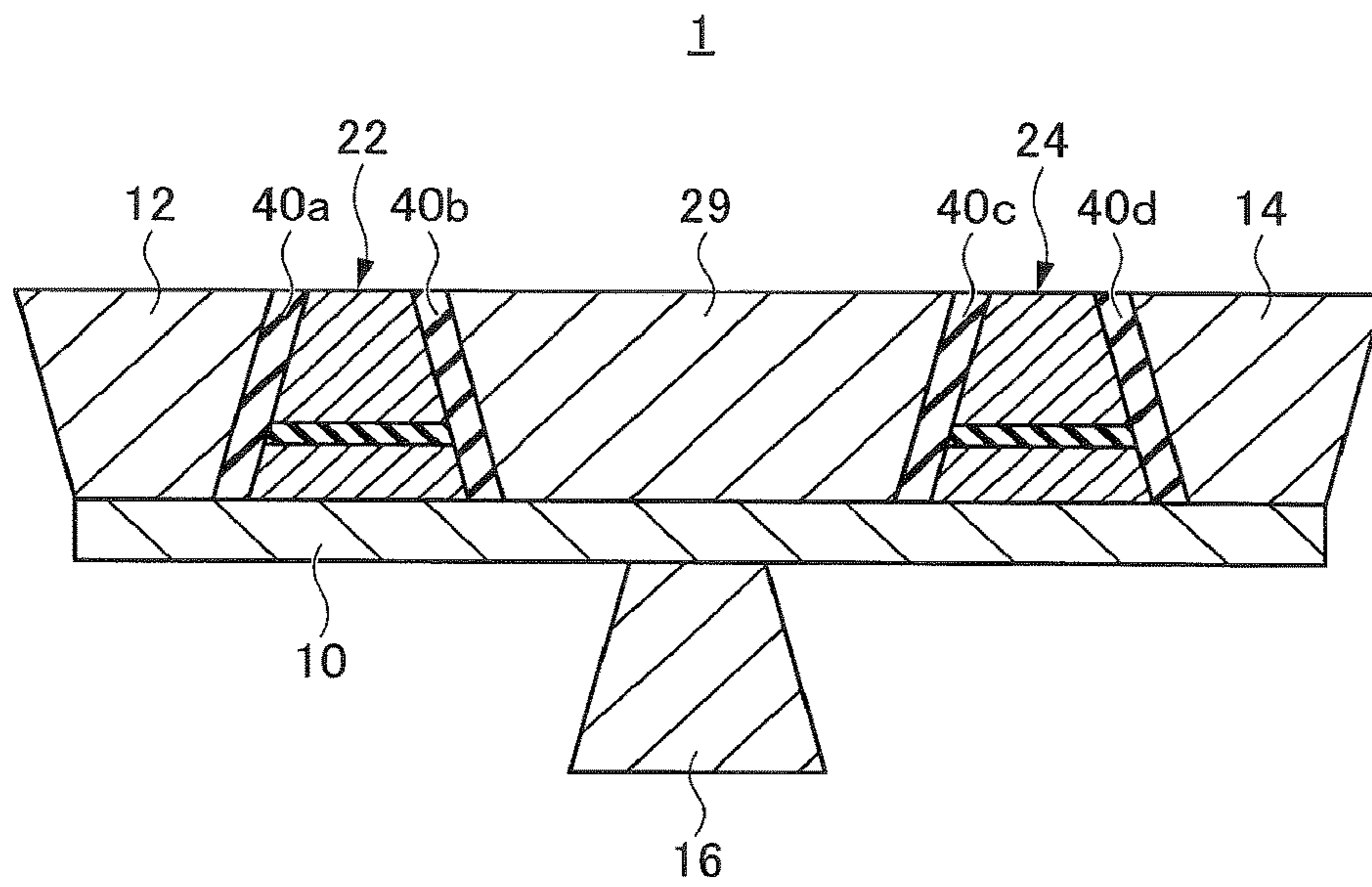


FIG. 65

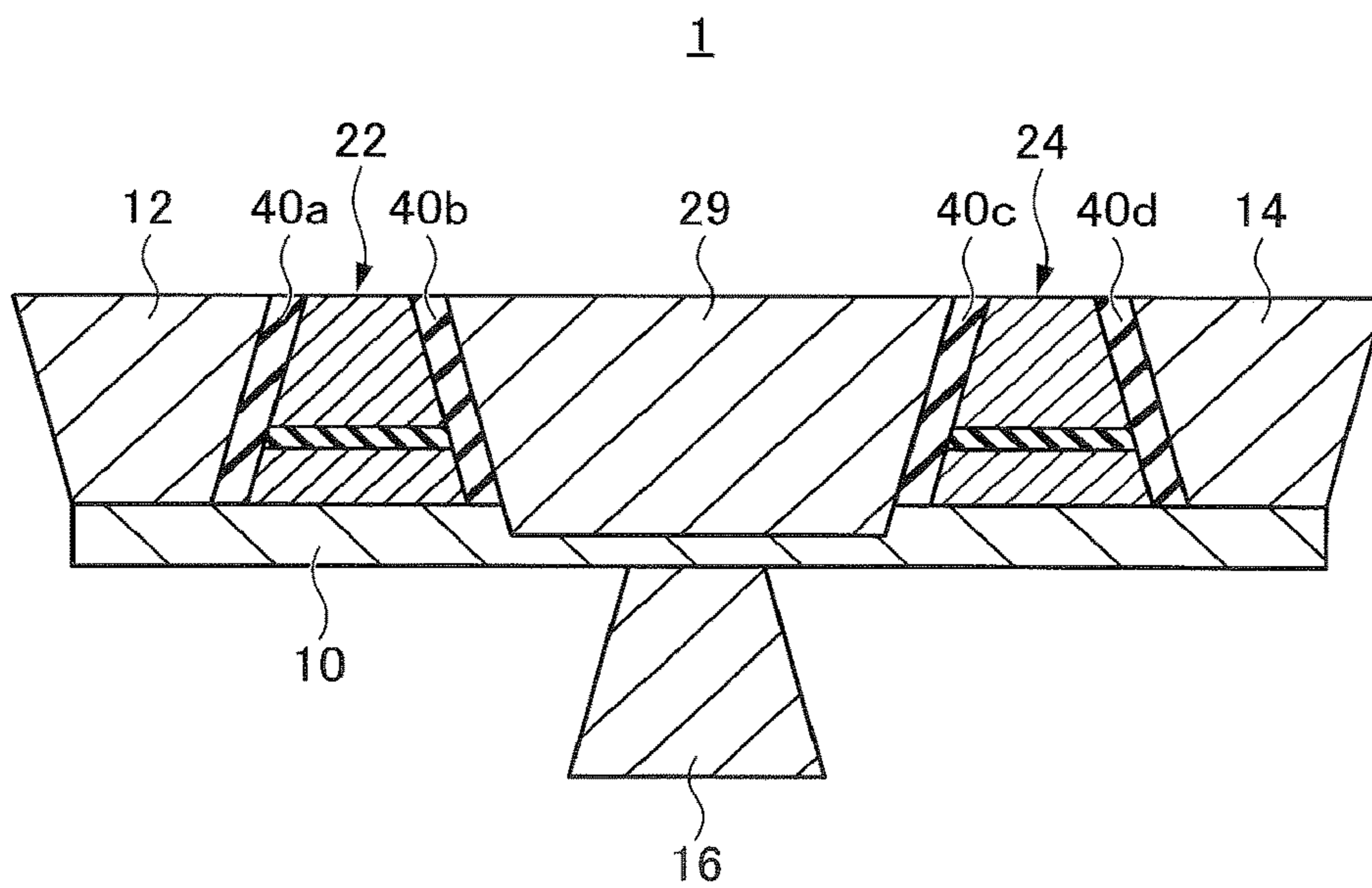


FIG. 66



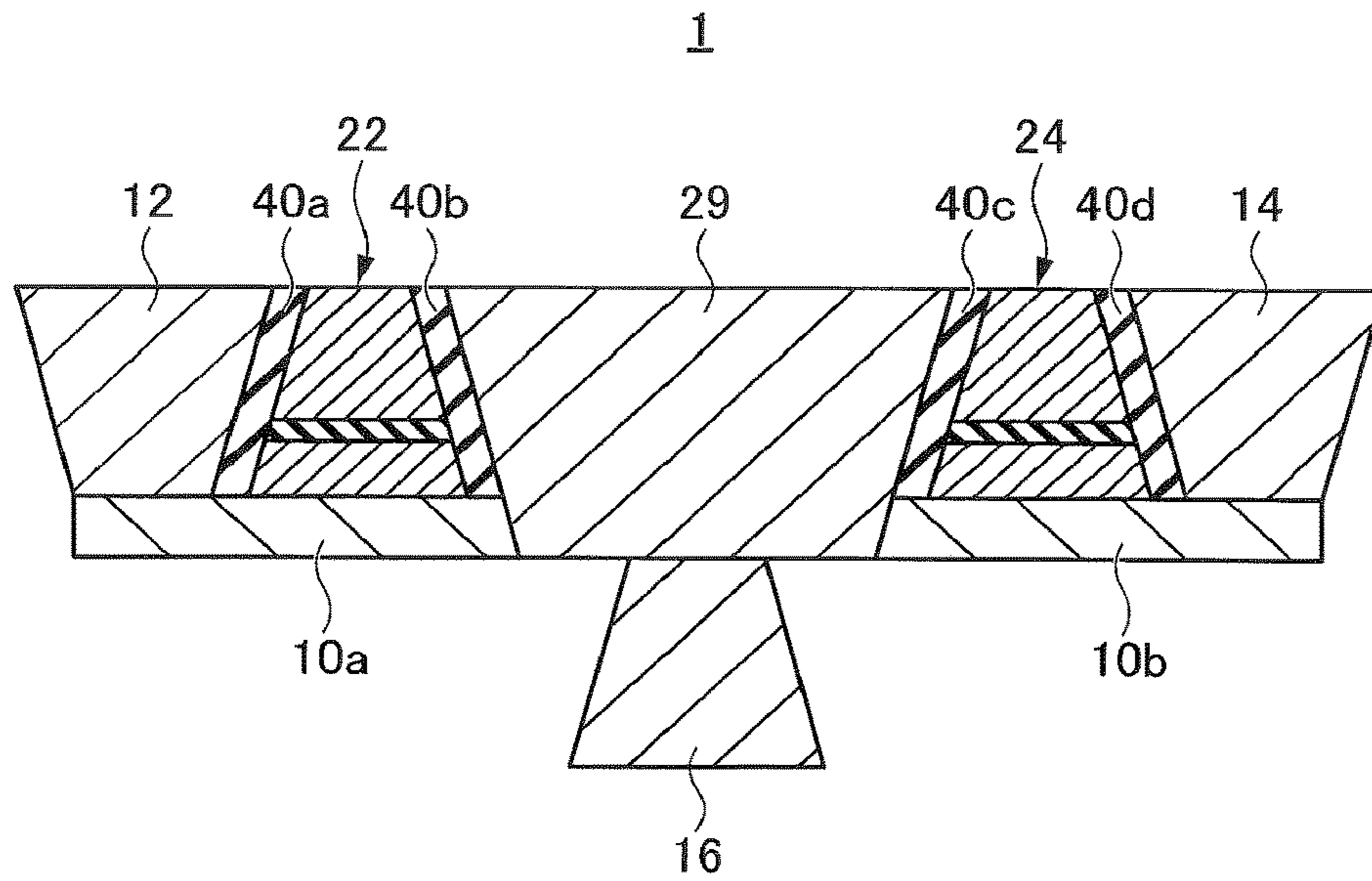


FIG. 67

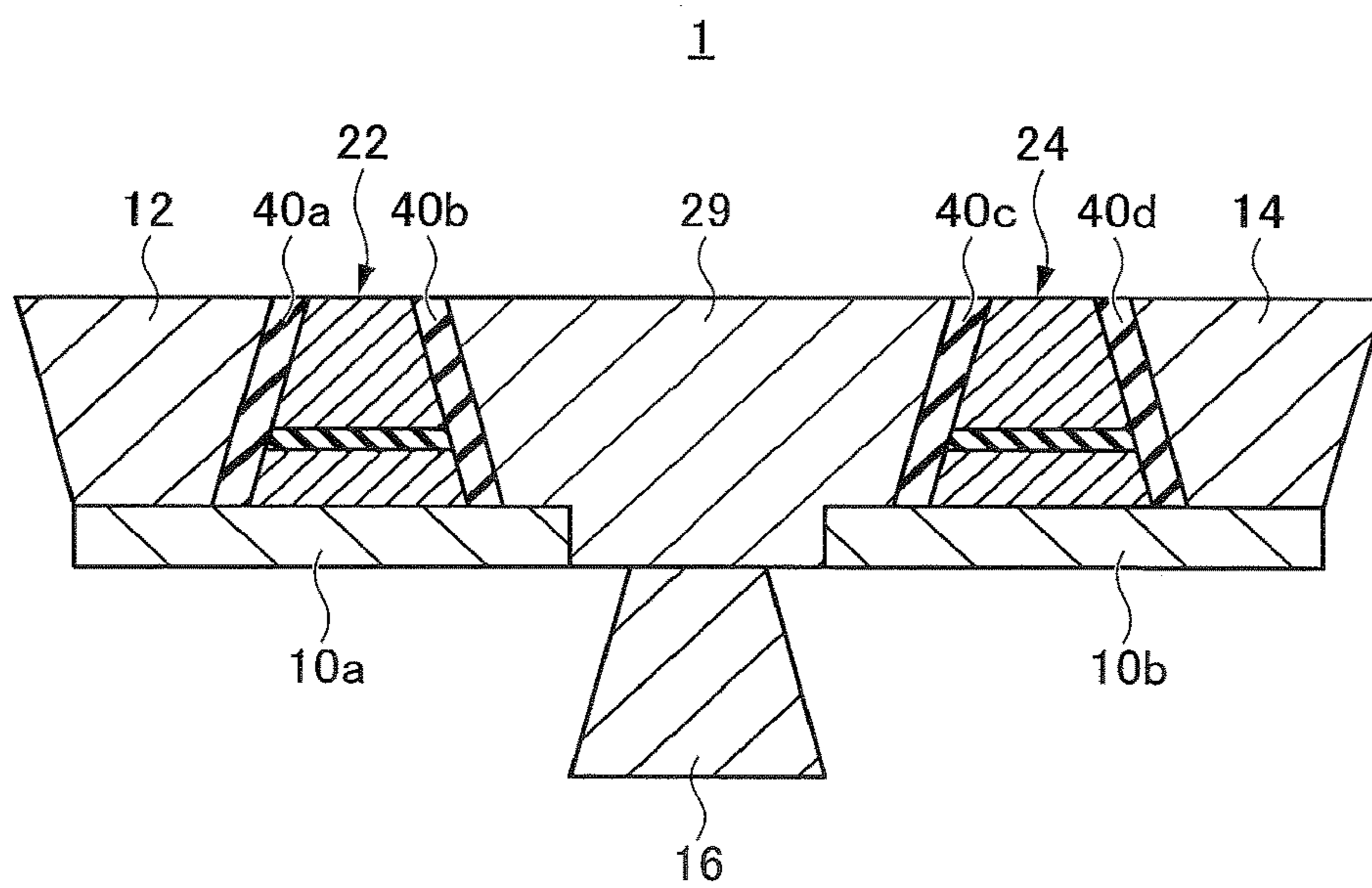


FIG. 68

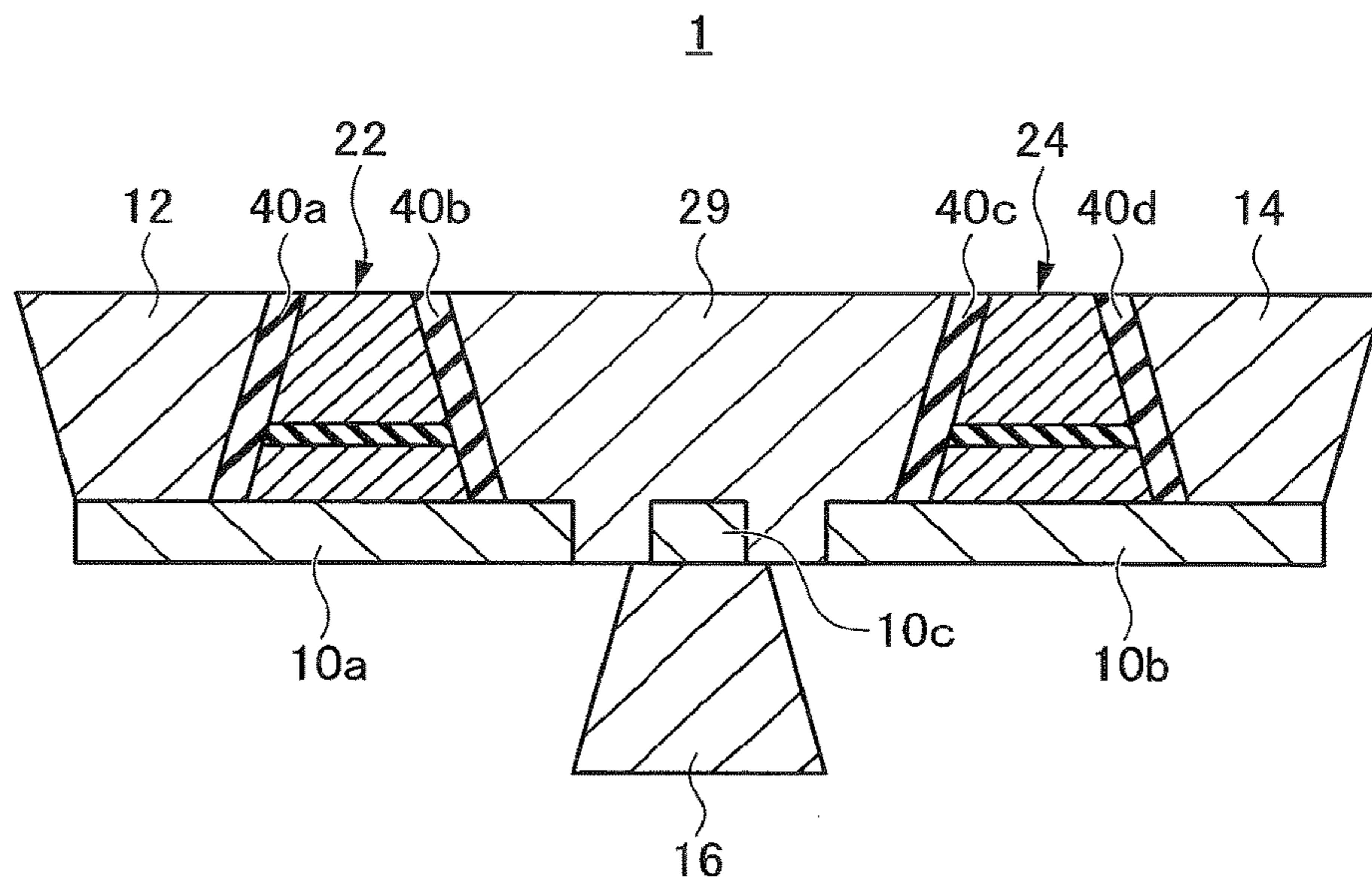


FIG. 69

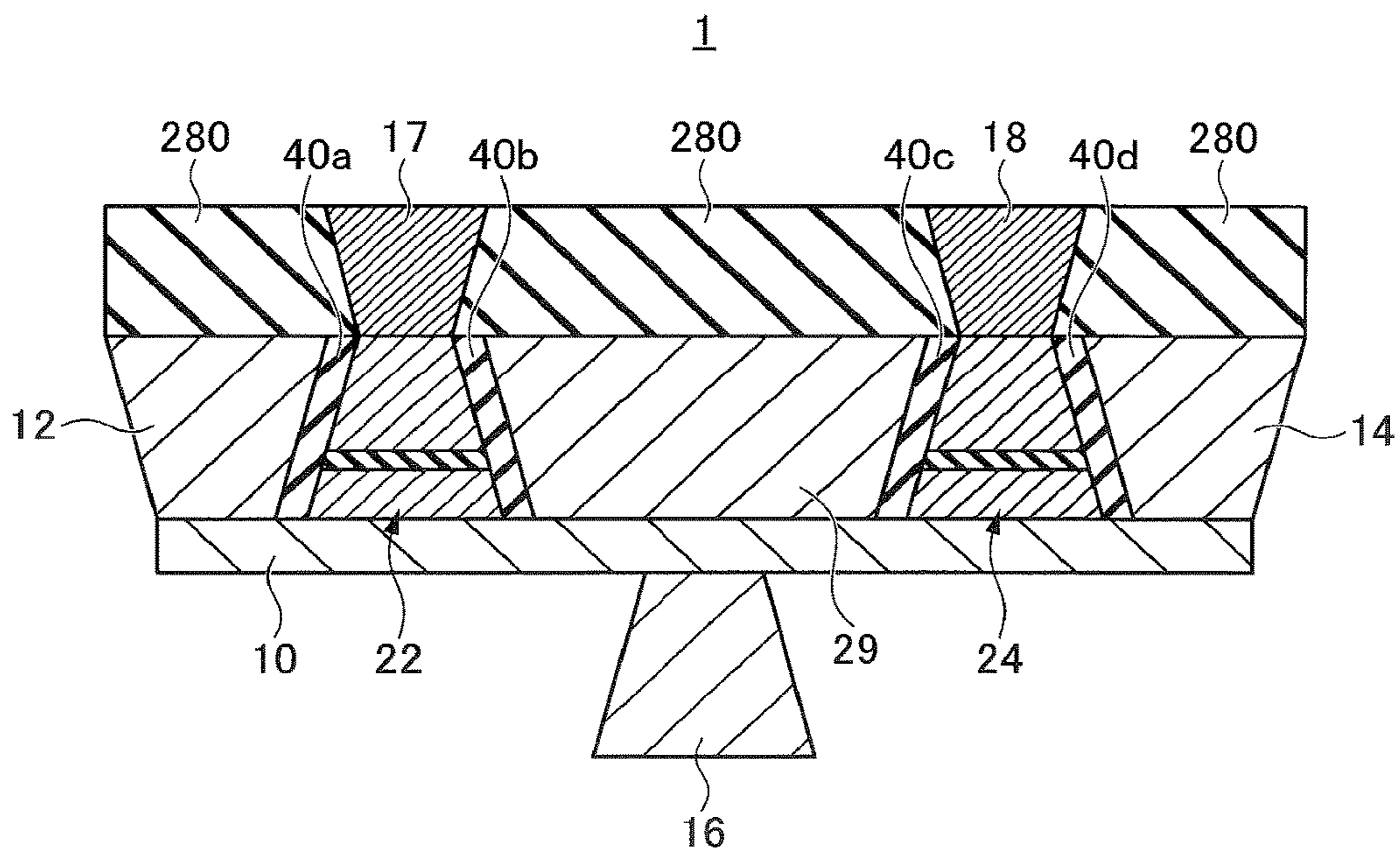


FIG. 70

## 1

## MAGNETIC MEMORY

CROSS REFERENCE TO RELATED  
APPLICATIONS

This application is based upon and claims the benefit of priority from the prior Japanese Patent Application No. 2016-244769, filed on Dec. 16, 2016, the entire contents of which are incorporated herein by reference.

## FIELD

Embodiments described herein relate generally to magnetic memories.

## BACKGROUND

Existing memories may be classified into volatile working memories (such as static random access memories (SRAMs) and dynamic random access memories (DRAMs)) and non-volatile storage memories (such as NAND flash memories and hard disk drives (HDDs)). The volatile memories consume large energy due to leakage current in the SRAMs and refresh current in the DRAMs.

In order to solve this problem, various kinds of nonvolatile memories have been considered as working memories that replace the SRAMs and the DRAMs.

The working memories, however, are accessed more often in an active state than in a standby state. Since a large writing charge (Qw) is required in the active state, energy required for a write operation increases. As a result, the energy saved during the standby state due to the nonvolatile characteristic is completely consumed in the active state, and therefore the total energy consumption is difficult to be decreased. This is called “nonvolatile memories’ historical dilemma.” No existing product has solved this problem.

Recently performed experimental simulations using best data may be solving the problem to reduce energy consumption, in which a STT (spin transfer torque)-MRAM (Magnetic Random Access Memory) is used as a lowest level cache memory (LLC (Last Level Cache)).

If a STT-MRAM is used as a cache memory in a layer higher than the LLC, however, the frequency at which it is accessed considerably increases. Therefore, considerable energy is consumed. As a result, the aforementioned energy consumption problem may not be solved.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram illustrating a memory cell of a magnetic memory according to a first embodiment.

FIG. 2 is a diagram illustrating a memory cell of a magnetic memory according to a first modification of the first embodiment.

FIG. 3 is a diagram illustrating a memory cell of a magnetic memory according to a second modification of the first embodiment.

FIG. 4 is a perspective view of a specific example of a magnetoresistive element included in the magnetic memory according to the first embodiment.

FIG. 5 is an explanatory diagram of an operation for writing data “1” to the magnetic memory according to the first embodiment.

FIG. 6 is an explanatory diagram of an operation for writing data “0” to the magnetic memory according to the first embodiment.

## 2

FIG. 7 is an explanatory diagram of a read operation in the magnetic memory according to the first embodiment.

FIG. 8 is a diagram showing a relationship between a voltage applied to a reference layer of a magnetoresistive element and a threshold current of the magnetoresistive element, obtained by a simulation.

FIG. 9A is a diagram showing hysteresis characteristics of resistance value relative to current value when a positive voltage is applied to a reference layer of a magnetoresistive element.

FIG. 9B is a diagram showing hysteresis characteristics of resistance value relative to current value when no voltage is applied to the reference layer of the magnetoresistive element.

FIG. 9C is a diagram showing hysteresis characteristics of resistance value relative to current value when a negative voltage is applied to the reference layer of the magnetoresistive element.

FIG. 10 shows a result of an experiment for obtaining a relationship between a voltage applied to a magnetoresistive element and a current flowing through a conductive layer, with which the magnetization is switched.

FIG. 11 is a cross-sectional view showing a memory cell of a magnetic memory according to a second embodiment.

FIG. 12 is a cross-sectional view showing a specific example of a structure of a perpendicular magnetization magnetoresistive element.

FIG. 13A is a cross-sectional view of a memory cell of a magnetic memory according to a third embodiment.

FIG. 13B is a plan view showing magnetization directions in storage layers of the memory cell according to the third embodiment.

FIG. 14A is a cross-sectional view showing a memory cell of a magnetic memory according to a fourth embodiment.

FIG. 14B is a plan view showing magnetization directions of storage layers of the memory cell according to the fourth embodiment.

FIG. 14C is a plan view showing the magnetization directions of the storage layers of the memory cell according to the fourth embodiment, when it is subjected to the influence of a stray magnetic field from a reference layer.

FIG. 14D is a plan view showing magnetization directions of storage layers of a memory cell according to a modification of the fourth embodiment.

FIG. 15A is an explanatory diagram of an operation for writing data “1” to a memory cell of a magnetic memory according to a fifth embodiment.

FIG. 15B is an explanatory diagram of an operation for writing data “0” to the memory cell of the magnetic memory according to the fifth embodiment.

FIG. 15C is an explanatory diagram of a read operation in the magnetic memory according to the fifth embodiment.

FIG. 16A is an explanatory diagram of an operation for writing data “1” to a memory cell of a magnetic memory according to a sixth embodiment.

FIG. 16B is an explanatory diagram of an operation for writing data “0” to the memory cell of the magnetic memory according to the sixth embodiment.

FIG. 17 is a cross-sectional view showing a memory cell of a magnetic memory according to a seventh embodiment.

FIG. 18 is a cross-sectional view showing a memory cell of a magnetic memory according to an eighth embodiment.

FIG. 19 is a cross-sectional view for explaining the effect of the memory cell according to the eighth embodiment.

FIG. 20 is a cross-sectional view for explaining the effect of the memory cell according to the eighth embodiment.

FIGS. 21 to 28 are cross-sectional views for explaining a method of manufacturing the memory cell according to the eighth embodiment.

FIG. 29 is a cross-sectional view of a memory cell manufactured by the method according to the eighth embodiment.

FIG. 30 is a cross-sectional view of a memory cell manufactured by another method according to the eighth embodiment.

FIGS. 31A to 31F are plan views for explaining a method of manufacturing a magnetic memory according to a ninth embodiment.

FIG. 32 is a plan view of a magnetic memory manufactured by the method according to the ninth embodiment.

FIG. 33 is a cross-sectional view of a memory cell according to a tenth embodiment.

FIG. 34 is a cross-sectional view of a magnetic memory according to a first modification of the tenth embodiment.

FIG. 35 is a cross-sectional view of a magnetic memory according to a second modification of the tenth embodiment.

FIG. 36 is a cross-sectional view of a magnetic memory according to a third modification of the tenth embodiment.

FIG. 37 is a cross-sectional view of a magnetic memory according to a fourth modification of the tenth embodiment.

FIG. 38 is a cross-sectional view of a magnetic memory according to an eleventh embodiment.

FIGS. 39 to 44 are cross-sectional views showing a method of manufacturing a magnetic memory according to a twelfth embodiment.

FIG. 45 is a cross-sectional view showing a magnetic memory manufactured by the method according to the twelfth embodiment.

FIG. 46 is a circuit diagram of a magnetic memory according to a thirteenth embodiment.

FIG. 47 is a circuit diagram showing a write operation in the magnetic memory according to the thirteenth embodiment.

FIG. 48 is a circuit diagram showing a read operation in the magnetic memory according to the thirteenth embodiment.

FIG. 49 is a circuit diagram of a magnetic memory according to a modification of the thirteenth embodiment.

FIG. 50 is a circuit diagram of a magnetic memory according to a fourteenth embodiment.

FIG. 51 is a circuit diagram of a magnetic memory according to a fifteenth embodiment.

FIG. 52 is a circuit diagram of a magnetic memory according to a sixteenth embodiment.

FIG. 53 is a circuit diagram of a magnetic memory according to a seventeenth embodiment.

FIG. 54 is a circuit diagram for explaining a write operation in the magnetic memory according to the seventeenth embodiment.

FIG. 55 is a circuit diagram for explaining a read operation in the magnetic memory according to the seventeenth embodiment.

FIG. 56 is a plan view of a magnetic memory according to an eighteenth embodiment.

FIG. 57 is a cross-sectional view of the magnetic memory according to the eighteenth embodiment taken along line A-A in FIG. 56.

FIG. 58 is a cross-sectional view of the magnetic memory according to the eighteenth embodiment taken along line B-B in FIG. 56.

FIG. 59 is a plan view of a magnetic memory according to a nineteenth embodiment.

FIG. 60 is a cross-sectional view of the magnetic memory according to the nineteenth embodiment taken along line A-A in FIG. 59.

FIG. 61 is a cross-sectional view showing a memory cell of a magnetic memory according to a twentieth embodiment.

FIG. 62 is a perspective view of the memory cell according to the twentieth embodiment.

FIG. 63 is a cross-sectional view showing a memory cell of a magnetic memory according to a twenty-first embodiment.

FIG. 64 is a cross-sectional view showing a memory cell of a magnetic memory according to a first modification of the twenty-first embodiment.

FIG. 65 is a cross-sectional view showing a memory cell of a magnetic memory according to a second modification of the twenty-first embodiment.

FIG. 66 is a cross-sectional view showing a memory cell of a magnetic memory according to a third modification of the twenty-first embodiment.

FIG. 67 is a cross-sectional view showing a memory cell of a magnetic memory according to a fourth modification of the twenty-first embodiment.

FIG. 68 is a cross-sectional view showing a memory cell of a magnetic memory according to a fifth modification of the twenty-first embodiment.

FIG. 69 is a cross-sectional view showing a memory cell of a magnetic memory according to a sixth modification of the twenty-first embodiment.

FIG. 70 is a cross-sectional view showing a memory cell of a magnetic memory according to a seventh modification of the twenty-first embodiment.

#### DETAILED DESCRIPTION

A magnetic memory according to an embodiment includes: a first terminal, a second terminal, and a third terminal; a first conductive layer including first to fifth regions, the second region being between the first region and the fifth region, the third region being between the second region and the fifth region, the fourth region being between the third region and the fifth region, the first region being electrically connected to the first terminal, the fifth region being electrically connected to the second terminal, and the third region being electrically connected to the third terminal; a first magnetoresistive element disposed corresponding to the second region, the first magnetoresistive element including a first magnetic layer, a second magnetic layer disposed between the second region and the first magnetic layer, a first nonmagnetic layer disposed between the first magnetic layer and the second magnetic layer, and a fourth terminal electrically connected to the first magnetic layer; a second magnetoresistive element disposed corresponding to the fourth region, the second magnetoresistive element including a third magnetic layer, a fourth magnetic layer disposed between the fourth region and the third magnetic layer, a second nonmagnetic layer disposed between the third magnetic layer and the fourth magnetic layer, and a fifth terminal electrically connected to the third magnetic layer; and a circuit configured to flow a write current between the first terminal and the third terminal and between the second terminal and the third terminal in a write operation.

Embodiments will now be described with reference to the accompanying drawings.

#### First Embodiment

A magnetic memory according to a first embodiment will be described with reference to FIGS. 1 to 7. The magnetic

## 5

memory according to the first embodiment includes at least one memory cell. FIG. 1 shows the configuration of the memory cell. The memory cell 1 includes a conductive layer 10, three terminals (electrodes) 12, 14, and 16 separately disposed on the conductive layer 10, and two magnetoresistive elements 22 and 24.

The terminal 16 is disposed in a region of the conductive layer 10 between the terminal 12 and the terminal 14. The terminals 12 and 14 are disposed on one face of the conductive layer 10, and the terminal 16 is disposed on another face of the conductive layer 10. The magnetoresistive element 22 is disposed on the conductive layer 10 between the terminal 12 and the terminal 16, and the magnetoresistive element 24 is disposed on the conductive layer 10 between the terminal 16 and the terminal 14. The magnetoresistive elements 22 and 24 are disposed on the one face of the conductive layer 10. Thus, the terminals 12 and 14 and the magnetoresistive elements 22 and 24 are disposed on the same face of the conductive layer 10.

The magnetoresistive element 22 includes a magnetic layer (storage layer) 22a disposed on the conductive layer 10, the magnetization direction of the magnetic layer 22a being changeable, a nonmagnetic layer 22b disposed on the magnetic layer 22a, and a magnetic layer (reference layer) 22c disposed on the nonmagnetic layer 22b, the magnetization direction of the magnetic layer 22c being fixed. The magnetization direction that is "changeable" means that the magnetization direction may be changed after a write operation is performed on the magnetoresistive element, and the magnetization direction that is "fixed" means that the magnetization direction is not changed after a write operation is performed on the magnetoresistive element. The magnetoresistive element 24 includes a magnetic layer 24a disposed on the conductive layer 10, the magnetization direction of the magnetic layer 24a being changeable, a nonmagnetic layer 24b disposed on the magnetic layer 24a, and a magnetic layer 24c disposed on the nonmagnetic layer 24b, the magnetization direction of the magnetic layer 24c being fixed. A terminal 17 is disposed on the magnetic layer 22c of the magnetoresistive element 22, and a terminal 18 is disposed on the magnetic layer 24c of the magnetoresistive element 24.

The terminals 12, 14, 16, 17, and 18 are electrically connected to a control circuit 100. A current is caused to flow or a voltage is applied to the terminals 12, 14, 16, 17, and 18 by the control circuit 100, as will be described later.

(First Modification)

A magnetic memory according to a first modification of the first embodiment will be described with reference to FIG. 2. FIG. 2 is a diagram illustrating the memory cell 1 of the magnetic memory according to the first modification. The memory cell 1 according to the first modification has a configuration obtained by disposing switches 491, 492, and 493 between the control circuit 100 and the terminals 12, 14, and 16, and switches 494 and 495 between the control circuit 100 and the terminals 17 and 18 in the memory cell 1 according to the first embodiment shown in FIG. 1.

(Second Modification)

A magnetic memory according to a second modification of the first embodiment will be described with reference to FIG. 3. FIG. 3 is a diagram illustrating the memory cell 1 of the magnetic memory according to the second modification. The memory cell 1 according to the second modification has a configuration obtained by removing the switch 492 and electrically connecting the terminal 12 and the terminal 14 in the memory cell according to the first modification shown in FIG. 2.

## 6

The respective elements of the memory cells will be described with reference to FIG. 4.

(Conductive Layer)

The conductive layer 10 contains a nonmagnetic material having a spin orbit interaction (spin Hall effect) or a Rashba effect, such as Ta, W, or Pt. If a write current  $I_w$  is caused to flow through the conductive layer 10 from right to left in FIG. 4, for example, electrons 11a with up spin flow in the upper side of the conductive layer 10, and electrons 11b with down spin flow in the lower side of the conductive layer 10 in a diffusion manner. If the write current  $I_w$  is caused to flow through the conductive layer 10 from left to right, as is opposite to the case shown in FIG. 4, for example, electrons 11b with down spin flow in the upper side of the conductive layer 10, and electrons 11a with up spin flow in the lower side of the conductive layer 10. The direction of the write current  $I_w$  flowing through the conductive layer 10 is controlled by the control circuit 100 shown in FIG. 1.

(Magnetoresistive Element)

FIG. 4 shows a specific example of the magnetoresistive elements 22 and 24. A magnetoresistive element 20 of the specific example has a multilayer structure including a magnetic layer (storage layer) 20a disposed on the conductive layer 10, the magnetization direction of the magnetic layer 20a being changeable, a nonmagnetic layer 20b disposed on the magnetic layer 20a, a magnetic layer (reference layer) 20c disposed on the nonmagnetic layer 20b, the magnetization direction of the magnetic layer 20c being fixed. The magnetoresistive element may be a magnetic tunnel junction (MTJ) element, in which the nonmagnetic layer 20b is an insulating layer, or a giant magneto-resistive (GMR) element in which the nonmagnetic layer 20b is a nonmagnetic metal layer. In FIGS. 1 to 4, each magnetoresistive element is an MTJ element, in which the magnetization direction of the storage layer and the magnetization direction of the reference layer are parallel to the film plane. Thus, each magnetoresistive element is an in-plane magnetization MTJ element, in which the magnetization direction is perpendicular to the stacking direction of the multilayer structure. The storage layer 20a is, for example, a CoFeB layer, and the nonmagnetic layer 20b is, for example, an MgO layer. The reference layer 20c may include, for example, a CoFeB layer 20c1, a Ru layer 20c2 disposed on the CoFeB layer 20c1, a CoFe layer 20c3 disposed on the Ru layer 20c2, and an antiferromagnetic layer 20c4 of IrMn, for example, which is disposed on the CoFe layer 20c3 to fix the magnetization direction of the reference layer 20c.

The reference layer 20c has a synthetic antiferromagnetic multilayer structure in which antiferromagnetic coupling of the CoFeB layer 20c1 and the CoFe layer 20c3 via the Ru layer 20c2 is caused. Thus, the magnetization direction of the CoFeB layer 20c1 and the magnetization direction of the CoFe layer 20c3 are antiparallel to each other.

Unlike the ones shown in FIGS. 1 to 4, if the magnetoresistive element is of perpendicular magnetization type, in which the magnetization direction of the storage layer 20a and the magnetization direction of the reference layer 20c are parallel to the stacking direction of the multilayer structure, the antiferromagnetic layer 20c4 may be removed. Although the magnetoresistive elements are disposed on the conductive layer 10 in FIGS. 1 to 4, they may be disposed under the conductive layer 10.

If a write current  $I_w$  is caused to flow through the conductive layer 10 of the magnetoresistive element 20 from right to left in FIG. 4, a spin current is generated in the conductive layer 10 by the electrons 11a with up spin and the electrons 11b with down spin. The spin current may exert a

spin torque on the storage layer **20a** to switch the magnetization direction of the storage layer **20a**. The magnetization of the storage layer **20a** is switched in opposite directions by whether the write current  $I_w$  is caused to flow from right to left or from left to right in the conductive layer **10**.

The magnetoresistive element **20** is patterned to have a rectangular top shape, and has a shape magnetic anisotropy. Therefore, the longitudinal direction is a stable magnetization direction in the storage layer and the reference layer. A stable magnetization direction in FIG. 1 is, for example, from the depth side to the front side, or from the front side to the depth side. This stability is called (longitudinal) uniaxial magnetic anisotropy. The uniaxial magnetic anisotropy is dependent on the aspect ratio of the rectangular shape, the thickness of the storage layer, and the magnetization of the magnetic layers. The write current threshold value  $I_{co}$ , which will be described later, is proportional to the uniaxial magnetic anisotropy.

(Write Operation)

A method of writing data to a memory cell according to the first embodiment and its first modification and second modification will be described with reference to FIGS. 5 and 6.

The magnetoresistive elements **22** and **24** of the memory cell **1** store information (data) as the magnetization directions of the storage layers **22a** and **24a**. In this embodiment and its modifications, the storage layers **22a** and **24a** of the magnetoresistive elements **22** and **24** store information having opposite magnetization directions. For example, FIG. 5 shows that information (data) "1" is stored, and FIG. 6 shows that information (data) "0" is stored. In FIGS. 5 and 6, the magnetization directions of the reference layer **22c** of the magnetoresistive element **22** and the reference layer **24c** of the magnetoresistive element **24** are from the depth side to the front side. In FIG. 5, the magnetization direction of the storage layer **22a** of the magnetoresistive element **22** is from the depth side to the front side, and the magnetization direction of the storage layer **24a** of the magnetoresistive element **24** is from the front side to the depth side. In FIG. 6, the magnetization direction of the storage layer **22a** of the magnetoresistive element **22** is from the front side to the depth side, and the magnetization direction of the storage layer **24a** of the magnetoresistive element **24** is from the depth side to the front side.

FIGS. 5 and 6 show that a transistor **33** is disposed on a semiconductor layer **120**. A terminal **33a**, which is one of the source and the drain, of the transistor **33** is connected to the terminal **16**, and a terminal **33b**, which is the other of the source and the drain, is connected to an electrode **37** disposed on the terminal **33b**. A gate electrode **33c** is disposed above the semiconductor layer **120** between the terminal **33a** and the terminal **33b**.

As shown in FIG. 5, when the data "1" is written, the transistor **33** is turned on and a write current  $I_w$  is caused to flow from the electrode **37** to the terminal **16**. The write current  $I_w$  further flows from the terminal **16** to the terminal **12** and the terminal **14** via the conductive layer **10**. This means that the current flowing through the conductive layer **10** below the storage layer **22a** of the magnetoresistive element **22** and the current flowing through the conductive layer **10** below the storage layer **24a** of the magnetoresistive element **24** are in opposite directions. As a result, the magnetization direction of the storage layer **22a** and the magnetization direction of the storage layer **24a** become antiparallel to each other. Thus, the storage layer **22a** of the magnetoresistive element **22** and the storage layer **24a** of the magnetoresistive element **24** store magnetizations with

opposite polarities. As a result, the magnetization directions of the storage layer **22a** and the reference layer **22c** of the magnetoresistive element **22** after the write operation become parallel to each other, and the magnetization directions of the storage layer **24a** and the reference layer **24c** of the magnetoresistive element **24** become antiparallel to each other. This means that data "1" is written. In this case, the magnetization directions of the storage layers **22a** and **24a** and the spin direction of polarized electrons that interacts with the magnetization directions of the storage layers **22a** and **24a** are in parallel or antiparallel relationship. Therefore, the magnetizations of the storage layers **22a** and **24a** are switched with precession.

As shown in FIG. 6, when the data "0" is written, the transistor **33** is turned on and the write current  $I_w$  is caused to flow from the terminals **12** and **14** to the terminal **16** and the electrode **37** via the conductive layer **10**. This means that the current flowing through the conductive layer **10** below the storage layer **22a** of the magnetoresistive element **22** and the current flowing through the conductive layer **10** below the storage layer **24a** of the magnetoresistive element **24** are in opposite directions. As a result, the magnetization direction of the storage layer **22a** and the magnetization direction of the storage layer **24a** become antiparallel to each other. Thus, the storage layer **22a** of the magnetoresistive element **22** and the storage layer **24a** of the magnetoresistive element **24** store magnetizations with opposite polarities. As a result, the magnetization directions of the storage layer **22a** and the reference layer **22c** of the magnetoresistive element **22** after the write operation become antiparallel to each other, and the magnetization directions of the storage layer **24a** and the reference layer **24c** of the magnetoresistive element **24** become parallel to each other. This means that data "0" is written. In this case, the magnetization directions of the storage layers **22a** and **24a** and the spin direction of polarized electrons that interacts with the magnetization directions of the storage layers **22a** and **24a** are in parallel or antiparallel relationship. Therefore, the magnetizations of the storage layers **22a** and **24a** are switched with precession.

(Read Operation)

A method of reading data from the memory cell **1** will be described below with reference to FIG. 7. In a read operation, the transistor **33** is first turned on. Subsequently, a voltage  $V$  is applied between the terminal **17** and the terminal **18** as shown in FIG. 7, and then a potential  $V_{read}$  at the terminal **16** is read. The terminal **17** is connected to a ground power supply. The voltage  $V$  is applied to the terminal **18**.

The magnetoresistive element has a low resistance  $R_{low}$  when the magnetizations of the reference layer and the storage layer are parallel to each other, and a high resistance  $R_{high}$  when the magnetizations of the reference layer and the storage layer are antiparallel to each other. If the memory cell **1** stores the data "1" as shown in FIG. 5, the potential  $V_{r1}$  at the terminal **16** is as follows:

$$V_{r1} = \{R_{low}/(R_{low} + R_{high})\} \times V.$$

If the memory cell **1** stores the data "0" as shown in FIG. 6, the potential  $V_{r2}$  at the terminal **16** is as follows:

$$V_{r2} = \{R_{high}/(R_{low} + R_{high})\} \times V.$$

Thus, the potential change  $\Delta V_r$  may be obtained by the following formula:

$$\Delta V_r = V_{r2} - V_{r1} = \{(R_{high} - R_{low}) / (R_{low} + R_{high})\} \times V.$$

The potential change  $\Delta V_r$  may be read by measuring the potential at the terminal **16**. Thus, a read operation may be

performed at a higher speed with a lower energy consumption as compared to a case where a constant current is caused to flow through a magnetoresistive element and a voltage between a storage layer and a reference layer of the magnetoresistive element is measured.

If the memory cell includes only one magnetoresistive element and a voltage is applied to the single magnetoresistive element, a large current flows when the magnetoresistive element has a low resistance, and a small current flows when the magnetoresistive element has a high resistance. Therefore, the potential change cannot be sensed.

The write current may be reduced in this embodiment by applying a voltage to the magnetoresistive elements **22** and **24** via the terminals **17** and **18**, respectively, and controlling the perpendicular magnetic anisotropy between the storage layers **22a** and **24a** and the nonmagnetic layers **22b** and **24b**. The write current may be reduced to about a half of the write current a case where no voltage is applied to the terminals **17** and **18** (for example, see JP 2016-153933 A). The writing charge (Qw) may be reduced to a minimum extent in this manner. The polarity of the voltage to be applied and whether the perpendicular magnetic anisotropy increases or decreases are determined by the materials of the nonmagnetic layers **22b** and **24b** and the storage layers **22a** and **24a**.

In a simulation described below, the anisotropy of the storage layer is assumed to increase when a positive voltage is applied to the reference layer, and to decrease when a negative voltage is applied.

FIGS. **8** to **9C** show simulation results proving the foregoing. FIG. **8** shows the simulation results of the threshold current  $I_{c0}$  at which the magnetization direction is switched in the storage layer of the magnetoresistive element when voltages +0.5 V, 0 V, and -0.5 V are applied to the reference layer of the magnetoresistive element and a current is caused to flow through the conductive layer. In FIG. **8**, the vertical axis represents the voltage applied to the reference layer of the magnetoresistive element, and the horizontal axis represents the threshold current  $I_{c0}$ .

The point  $P_1$  in FIG. **8** indicates that when a voltage +0.5 V is applied to the reference layer of the magnetoresistive element, the magnetization direction of the storage layer changes from an antiparallel (AP) state to a parallel (P) state relative to the magnetization direction of the reference layer, and the point  $P_2$  indicates that when a voltage +0.5 V is applied to the reference layer of the magnetoresistive element, the magnetization direction of the storage layer changes from the parallel (P) state to the antiparallel (AP) state relative to the magnetization direction of the reference layer.

The point  $P_3$  indicates that when a voltage 0 V is applied to the reference layer of the magnetoresistive element, the magnetization direction of the storage layer changes from the antiparallel (AP) state to the parallel (P) state relative to the magnetization direction of the reference layer, and the point  $P_4$  indicates that when a voltage 0 V is applied to the reference layer of the magnetoresistive element, the magnetization direction of the storage layer changes from the parallel (P) state to the antiparallel (AP) state relative to the magnetization direction of the reference layer.

The point  $P_5$  indicates that when a voltage -0.5 V is applied to the reference layer of the magnetoresistive element, the magnetization direction of the storage layer changes from the antiparallel (AP) state to the parallel (P) state relative to the magnetization direction of the reference layer, and the point  $P_6$  indicates that when a voltage -0.5 V is applied to the reference layer of the magnetoresistive element, the magnetization direction of the storage layer

changes from the parallel (P) state to the antiparallel (AP) state relative to the magnetization direction of the reference layer. The broken line connecting the points  $P_1$ ,  $P_3$ , and  $P_5$  indicates the changes in threshold current  $I_{c0}$  by which the magnetoresistive element changes from the AP state to the P state when the voltage applied to the reference layer of the magnetoresistive element is changed between +0.5 V and -0.5 V. The broken line connecting the points  $P_2$ ,  $P_4$ , and  $P_6$  indicates the changes in threshold current  $I_{c0}$  by which the magnetoresistive element changes from the P state to the AP state when the voltage applied to the reference layer of the magnetoresistive element is changed between +0.5 V and -0.5 V.

FIGS. **9A** to **9C** each show hysteresis curves when a voltage selected from +0.5 V, 0 V, and -0.5 V is applied to the reference layer of the magnetoresistive element. The vertical axis of each hysteresis curve diagram indicates the resistance R of the magnetoresistive element, and the horizontal axis represents the current I flowing through the conductive layer. The points  $P_1$  to  $P_6$  in FIGS. **9A** to **9C** correspond to the points  $P_1$  to  $P_6$  shown in FIG. **8**, respectively. As can be understood from FIGS. **8** to **9C**, applying a higher positive voltage to the reference layer of the magnetoresistive element leads to a lower threshold current  $I_{c0}$  than the threshold current when no voltage is applied. On the contrary, applying a lower negative voltage to the reference layer of the magnetoresistive element leads to a higher threshold current  $I_{c0}$  than the threshold current when no voltage is applied.

FIG. **10** shows a result of an experiment for obtaining a relationship between a voltage applied to the magnetoresistive element and a value  $I_{SO,switching}$  of a current flowing through the conductive layer, at which the magnetization switching occurs, in the memory cell according to the first embodiment. In this experiment, a combination of MgO and CoFeB is used to form the combination of the nonmagnetic material layer and the storage layer. With this combination of materials, the anisotropy of the storage layer is decreased when a positive voltage is applied to the reference layer, and increased when a negative voltage is applied.

The vertical axis in FIG. **10** represents voltage  $V_{MTJ}$  applied to the magnetoresistive element, and the horizontal axis represents current  $I_{SO,switching}$  flowing through the conductive layer, with which magnetization switching occurs. The region denoted by "P" in FIG. **10** indicates that the magnetization direction of the storage layer is parallel to the magnetization direction of the reference layer of the magnetoresistive element, and the region denoted by "AP" indicates that the magnetization direction of the storage layer is antiparallel to the magnetization direction of the reference layer in the magnetoresistive element. The current I flowing through the conductive layer is measured by the pulse width number ms, and the absolute value of the current I may be lower than the value of the threshold current  $I_{c0}$  on the ns order in FIG. **10**. However, the changes in the threshold current  $I_{c0}$  when a voltage is applied are the same as the result of the simulation for the most part.

As described above, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memories according to the first embodiment and its modifications.

#### Second Embodiment

A magnetic memory according to a second embodiment will be described with reference to FIG. **11**. The magnetic memory according to the second embodiment includes at

## 11

least one memory cell. FIG. 11 shows a cross-sectional view of the memory cell. The memory cell 1 according to the second embodiment is obtained by replacing the magnetoresistive elements 22 and 24 of the memory cell 1 according to the first embodiment shown in FIG. 5 with perpendicular magnetization magnetoresistive elements. Therefore, the magnetization direction 221 of the storage layer 22a of the magnetoresistive element 22 and the magnetization direction 241 of the storage layer 24a of the magnetoresistive element 24 are parallel to the stacking direction of the magnetoresistive element 1. In this embodiment, a multilayer structure including a nonmagnetic layer 13a and a magnetic layer 13b is disposed between the conductive layer 10 and the terminal 12, and a multilayer structure including a nonmagnetic layer 15a and a magnetic layer 15b is disposed between the conductive layer 10 and the terminal 14.

The magnetic layer 13b and the magnetic layer 15b have an in-plane magnetization (in-plane magnetic anisotropy) as shown in FIG. 11, and apply a biased magnetic field 210 to the storage layer 22a and the storage layer 24a. Having an in-plane magnetic anisotropy means that a component of the magnetization of a magnetic layer in a direction perpendicular to the stacking direction is greater than a component in the stacking direction.

If a current magnetic field is used as the biased magnetic field, energy consumption is increased. For example, several tens  $\mu\text{A}$  of current would generate only several Oe of magnetic field. Due to this, the error rate in a write operation cannot be reduced satisfactorily. Therefore, thin-film permanent magnets are used as the magnetic layer 13b and the magnetic layer 15b in this embodiment to obtain a magnetic field of more than several tens Oe.

In the second embodiment, when the write currents  $I_w$  flow through the conductive layer 10, the magnetization directions of the storage layers 22a and 24a are perpendicular to the spin direction of spin polarized electron. Therefore, the magnetizations of the storage layers 22a and 24a directly rotate without precession. Thus, the write operation is performed in a direct mode.

In the direct mode of the write operation, the magnetizations of the storage layers 22a and 24a may be rotated to an extent, but may not be switched to opposite directions. The biased magnetic field applied to the storage layers 22a and 24a using the magnetic layers 13b and 15b including the thin-film permanent magnets may cause the magnetization switching in the storage layers 22a and 24a so that the magnetizations in these layers are directed to the opposite directions at a low error rate, about  $1 \times 10^{-9}$ . As a result, a write operation may be performed according to the principle of determinism.

In a write operation in the direct mode, the write current with short pulses (having a pulse width of 3 ns or less) is smaller than a write current in a write operation using precession (for example, see K-S. Lee, et al., Appl. Phys. Lett. 104, 072413 (2014)). As a result, the writing charge ( $Q_w = I_w \times t_p$ , where  $t_p$  is the pulse width of the write current  $I_w$ ) may be reduced.

The write current may further be reduced by applying a voltage to the magnetoresistive elements 22 and 24 to control the interface magnetic anisotropy between the storage layers 22a and 24a and the nonmagnetic layers 22b and 24b.

FIG. 12 shows a specific example of a perpendicular magnetization magnetoresistive element that may be used as the magnetoresistive elements 22 and 24 according to the second embodiment. The magnetoresistive element 20A of

## 12

the specific example has a multilayer structure including a storage layer 20a of CoFeB, for example, disposed on the conductive layer 10, a nonmagnetic layer 20b of MgO, for example, disposed on the storage layer 20a, and a reference layer 20c disposed on the nonmagnetic layer 20b. The reference layer 20c includes, for example, a CoFeB layer 20c1, a Ru layer 20c2 disposed on the CoFeB layer 20c1, and a (Co/Pt) multilayer structure 20c3 having a perpendicular magnetic anisotropy disposed on the Ru layer 20c2. The perpendicular magnetic anisotropy here means that a component in the stacking direction of the magnetization of a magnetic layer is greater than a component in a direction perpendicular to the stacking direction when no external magnetic field is applied. The reference layer 20c has a synthetic antiferromagnetic multilayer structure in which the CoFeB layer 20c1 and the (Co/Pt) multilayer structure 20c3 are in an antiferromagnetic coupling relationship via the Ru layer 20c2. In the perpendicular magnetization magnetoresistive element 20A, the magnetization of the storage layer is directed to be perpendicular by the perpendicular magnetic anisotropy generated at the MgO interface.

A write operation and a read operation of the magnetic memory according to the second embodiment are performed in the same manner as those of the magnetic memory according to the first embodiment.

As described above, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the second embodiment.

## Third Embodiment

A magnetic memory according to a third embodiment will be described with reference to FIGS. 13A and 13B. The magnetic memory according to the third embodiment includes at least one memory cell. FIG. 13A is a cross-sectional view of the memory cell.

The memory cell 1 according to the third embodiment is obtained by replacing the magnetoresistive elements 22 and 24 of the memory cell 1 according to the first embodiment shown in FIG. 5 with magnetoresistive elements with an in-plane magnetic anisotropy. Thus, the magnetization direction 222 of the storage layer 22a included in the magnetoresistive element 22 and the magnetization direction 242 of the storage layer 24a included in the magnetoresistive element 24 are substantially perpendicular to the stacking direction of the magnetoresistive element 1, as shown in FIGS. 13A and 13B.

In this embodiment, magnetic layers 23 and 25 are disposed on the reference layers 22c and 24c of the magnetoresistive elements 22 and 24, respectively. FIG. 13B is a plan view showing the magnetization directions 222 and 242 of the storage layers 22a and 24a.

As shown in FIG. 13A, the magnetic layer 23 and the magnetic layer 25 have a perpendicular magnetization (perpendicular magnetic anisotropy), and apply a biased magnetic field 212 that is perpendicular to the stacking direction to the storage layer 22a and the storage layer 24a. Thin-film permanent magnets may be used as the magnetic layer 23 and the magnetic layer 25.

In the third embodiment, when a write current  $I_w$  flows through the conductive layer 10, the magnetization directions of the storage layers 22a and 24a are perpendicular to the spin direction of interacting spin-polarized electrons. Therefore, the magnetizations of the storage layers 22a and 24a directly rotate without precession. Thus, a deterministic write operation is performed by the biased magnetic field



## 13

212 caused by the magnetic layer 23 and the magnetic layer 25 of thin-film permanent magnets. The writing charge  $Q_w$  ( $=I_w \times t_p$ ) may be reduced, similarly to the second embodiment.

The write operation and the read operation of the magnetic memory according to the third embodiment are performed in the same manner as those of the magnetic memory according to the first embodiment.

As described above, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the third embodiment.

The write current may further be reduced by applying a voltage to the magnetoresistive elements 22 and 24 to control the interface magnetic anisotropy between the storage layers 22a and 24a and the nonmagnetic layers 22b and 24b in the write operation of the magnetic memory according to the third embodiment.

## Fourth Embodiment

A magnetic memory according to a fourth embodiment will be described with reference to FIGS. 14A and 14B. The magnetic memory according to the fourth embodiment includes at least one memory cell. FIG. 14A is a cross-sectional view of the memory cell.

The memory cell 1 according to the fourth embodiment has the same structure as the memory cell 1 according to the first embodiment shown in FIG. 5 except for the magnetization directions of the storage layers 22a and 24a included in the magnetoresistive elements 22 and 24. Thus, unlike the second and third embodiments, no biased magnetic field is applied to the storage layers 22a and 24a in the fourth embodiment. In the first to fourth embodiments, the terminal 12 and the terminal 14 are disposed to be separated from each other in a direction along which the conductive layer 10 extends. Thus, a current flows through the conductive layer 10 between the terminal 12 and the terminal 14 in a direction along which the conductive layer 10 extends.

FIG. 14B shows the magnetization directions of the storage layers 22a and 24a included in the memory cell according to the fourth embodiment. The magnetizations 221 and 241 of the storage layers 22a and 24a are inclined to make an angle  $\Theta$  ( $>0^\circ$ ) with the direction 251 of a current flowing between the terminal 12 and the terminal 14, as shown in FIG. 14B. According to experiments, the angle  $\Theta$  is preferably about  $15^\circ$ , and less than  $45^\circ$ . This arrangement causes the torque exerted on the magnetizations of the storage layers 22a and 24a to have a component in a direction of the easy magnetization axis of the magnetoresistive elements 22 and 24, and enables a deterministic write operation in which magnetizations with opposite polarities are written. Similarly to the second embodiment, the writing charge may be reduced in the fourth embodiment.

The write operation and the read operation of the magnetic memory according to the fourth embodiment are performed in the same manner as those of the magnetic memory according to the first embodiment.

In the fourth embodiment, the magnetization of the storage layer 22a is directed toward upper right and the magnetization of the storage layer 24a is directed toward lower left in FIG. 14B. If the magnetizations of the storage layers 22a and 24a are affected by a stray magnetic field from the reference layers 22c and 24c in the fourth embodiment, the magnetizations have components in the hard magnetization axis direction due to the influence of the stray magnetic field  $H_r$  as shown in FIG. 14C. As a result, the magnetization of

## 14

the storage layer 22a is directed toward upper right, and the magnetization of the storage layer 24a is directed toward upper left.

As described above, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the fourth embodiment.

(Modification)

In the fourth embodiment, the magnetization direction of the storage layers 22a and 24a is set to make an angle  $\Theta$  with the direction of the current flowing through the conductive layer 10. The same effect can be obtained by tilting the magnetization directions of the storage layers 22a and 24a relative to the direction of the current flowing through the conductive layer 10. FIG. 14D shows this state, in which the terminal 12 and the terminal 14 are separately disposed on a diagonal line of the conductive layer 10, and the magnetizations of the storage layer 22a and the storage layer 24a are set to be in a direction parallel to the direction along which the conductive layer 10 extends.

This causes a current flowing through the conductive layer 10 between the terminal 12 and the terminal 14 to be directed to be in a direction 251, which is parallel to the diagonal line of the conductive layer 10. As a result, the magnetizations of the storage layer 22a and the storage layer 24a are inclined to make an angle  $\Theta$  relative to the direction 251 of the current.

Similarly to the fourth embodiment, the writing charge may be reduced, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the modification of the fourth embodiment.

The write current may further be reduced in the fourth embodiment and its modification by applying a voltage to the magnetoresistive elements 22 and 24 to control the interface magnetic anisotropy between the storage layers 22a and 24a and the nonmagnetic layers 22b and 24b in the write operation.

## Fifth Embodiment

A magnetic memory according to a fifth embodiment will be described with reference to FIGS. 15A to 15C. The magnetic memory according to the fifth embodiment includes at least one memory cell. FIGS. 15A and 15B show the memory cell. FIG. 15A is an explanatory diagram illustrating a case where data "1" is written to the memory cell 1, and FIG. 15B is an explanatory diagram illustrating a case where data "0" is written to the memory cell 1.

The memory cell 1 according to the fifth embodiment has a configuration in which a multilayer structure including a nonmagnetic layer 19a and a magnetic layer 19b of a thin-film permanent magnet is disposed between the conductive layer 10 and the terminal 16 in the memory cell 1 according to the first embodiment shown in FIG. 5. In the fifth embodiment, the magnetoresistive elements 22 and 24 are of perpendicular magnetization type, and the magnetic layer 19b has a magnetization in a direction from the terminal 16 to the conductive layer 10. When the data "1" is written, the magnetization of the storage layer 22a included in the magnetoresistive element 22 is directed upward in the drawings, and the magnetization of the storage layer 24a included in the magnetoresistive element 24 is directed downward (FIG. 15A). When data "0" is written, the magnetization of the storage layer 22a included in the magnetoresistive element 22 is directed downward in the drawings,

## 15

and the magnetization of the storage layer **24a** included in the magnetoresistive element **24** is directed upward (FIG. **15B**).

In the case of FIG. **15A** illustrating the fifth embodiment, the write current  $I_w$  flows from the terminal **12** to the terminal **14**, and in the case of FIG. **15B**, the write current  $I_w$  flows from the terminal **14** to the terminal **12**. In both cases, a torque in the same direction is exerted by the write current to the magnetoresistive elements **22** and **24**.

However, the directions of biased magnetic fields **214a** and **214b** from the magnetic layer **19b** of a thin-film permanent magnet having a perpendicular magnetization are opposite in the magnetoresistive element **22** and the magnetoresistive element **24**. For example, in FIG. **15A**, the direction is to the left in the magnetoresistive element **22**, and to the right in the magnetoresistive element **24**. Thus, writing magnetizations with opposite polarities in a deterministic manner is made possible.

A read operation is performed by applying a voltage  $V$  between the terminal **18** and the terminal **17**, and reading the potential of the terminal **16** via the electrode **37**, as shown in FIG. **15C**. That is to say, similarly to the first embodiment, the voltage  $V$  is applied between the magnetoresistive element **24** and the magnetoresistive element **22**, and the potential of the terminal **16** is read via the electrode **37**.

Similarly to the first embodiment, energy consumption may be reduced and write and read operation may be performed at a high speed in the magnetic memory according to the fifth embodiment.

The write current may further be reduced in the fifth embodiment by applying a potential to the reference layers of the magnetoresistive element **22** and the magnetoresistive element **24** via the terminal **17** and the terminal **18** to control the interface magnetic anisotropy between the storage layers **22a** and **24a** and the nonmagnetic layers **22b** and **24b**.

## Sixth Embodiment

A magnetic memory according to a sixth embodiment will be described with reference to FIGS. **16A** and **16B**. The magnetic memory according to the sixth embodiment includes at least one memory cell. FIGS. **16A** and **16B** show the memory cell. FIG. **16A** is an explanatory diagram in a case where data "1" is written to the memory cell **1**, and FIG. **16B** is an explanatory diagram in a case where data "0" is written to the memory cell **1**.

A transistor **31** and a transistor **32** are separately disposed on a semiconductor layer **120** in the memory cell **1** according to the sixth embodiment. The transistor **31** has a source and a drain, one of which is connected to the terminal **12** and the other is connected to the electrode **38**. The terminal **12** is disposed to be at a more distance from the transistor **32** than the electrode **38**. The transistor **32** has a source and a drain, one of which is connected to the terminal **14** and the other is connected to the electrode **39**. The terminal **14** is disposed to be at a more distance from the transistor **31** than the electrode **39**.

A conductive layer **10A** that extends toward the transistor **32** side is disposed above the transistor **31**, one end of the conductive layer **10A** being connected to the terminal **12**. A conductive layer **10B** that extends toward the transistor **31** side is disposed above the transistor **32**, one end of the conductive layer **10B** being connected to the terminal **14**. The other end of the conductive layer **10A** and the other end of the conductive layer **10B** are electrically connected to each other by the terminal **16**. The terminal **16** is disposed on the side opposite to the terminal **12** relative to the

## 16

conductive layer **10A**, and on the opposite side to the terminal **14** relative to the conductive layer **10B**. The materials of the conductive layer **10A** and the conductive layer **10B** are selected so that the directions of spins accumulated in upper portions of these layers are opposite to each other. In other words, in the sixth embodiment, a sign of a spin Hall angle of the conductive layer **10A** is different from a sign of a spin Hall angle of the conductive layer **10B**.

The magnetoresistive element **22** is disposed on the conductive layer **10A** between the terminal **12** and the terminal **16**. The magnetoresistive element **22** is on the same side of the conductive layer **10A** as the terminal **16**. The magnetoresistive element **24** is disposed on the conductive layer **10B** between the terminal **14** and the terminal **16**. The magnetoresistive element **24** is on the same side of the conductive layer **10B** as the terminal **16**. The terminals **17** and **18** are disposed on the reference layers of the magnetoresistive elements **22** and **24**, respectively.

When data "1" is written to the memory cell **1**, a write current  $I_w$  is caused to flow from the terminal **12** to the terminal **14** via the conductive layer **10A**, the terminal **16**, and the conductive layer **10B**, as shown in FIG. **16A**. When data "0" is written to the memory cell **1**, the write current  $I_w$  is caused to flow from the terminal **14** to the terminal **12** via the conductive layer **10B**, the terminal **16**, and the conductive layer **10A**, as shown in FIG. **16B**. In both cases, the directions of the spins accumulated in the conductive layer **10A** and the conductive layer **10B** immediately below the magnetoresistive elements **22** and **24** are opposite to each other. Therefore, data with opposite polarities are written to the storage layers **22a** and **24a** of the magnetoresistive elements **22** and **24**.

A read operation is performed by applying a voltage between the terminal **17** and the terminal **18**, and reading the potential of the terminal **16**, as in the case of the first embodiment.

Similarly to the first embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the sixth embodiment.

The write current may further be reduced in the sixth embodiment by applying a potential to the reference layers of the magnetoresistive element **22** and the magnetoresistive element **24** via the terminal **17** and the terminal **18** to control the interface magnetic anisotropy between the storage layers **22a** and **24a** and the nonmagnetic layers **22b** and **24b**.

## Seventh Embodiment

A magnetic memory according to a seventh embodiment will be described with reference to FIG. **17**. The magnetic memory according to the seventh embodiment includes at least one memory cell. FIG. **17** is a cross-sectional view of the memory cell.

The memory cell **1** according to the seventh embodiment has a configuration in which the magnetoresistive element **22** and the magnetoresistive element **24** of the memory cell **1** according to the sixth embodiment shown in FIG. **16A** are stacked in order to reduce the cell size.

In the memory cell **1**, the terminal **12** is disposed on the lower surface of the conductive layer **10A** at one end of the conductive layer **10A**. The magnetoresistive element **22** and the terminal **16** (also referred conductive layer **16**) are disposed on the top surface of the conductive layer **10A**. One end of the conductive layer **16** is connected to the top surface at the other end of the conductive layer **10A**. The magnetoresistive element **22** is disposed on the top surface of the

17

conductive layer 10A between the one end and the other end of the conductive layer 10A. The terminal 17 is disposed on the magnetoresistive element 22. The

The other end of the conductive layer 16 is connected to the lower surface of the conductive layer 10B at one end of the conductive layer 10B. The magnetoresistive element 24 and the terminal 14 are disposed on the top surface of the conductive layer 10B. The terminal 14 is connected to the top surface of the conductive layer 10B at the other end of the conductive layer 10B. The magnetoresistive element 24 is disposed on the top surface of the conductive layer 10B between the one end and the other end of the conductive layer 10B. The terminal 18 is disposed on the magnetoresistive element 24. The conductive layer 10A, the conductive layer 10B, and the conductive layer 16 may be different from each other, or may be integrated as a single conductive layer.

The terminals 12, 14, 16, 17, and 18 are connected to the control circuit 100, and supplied with a current or a potential by the control circuit 100.

The write operation is performed in the same manner as those according to the sixth embodiment. In other words, a write current flows between the terminal 12 and the terminal 14. And like the sixth embodiment, the directions of the spins accumulated in the conductive layer 10A and the conductive layer 10B immediately below the magnetoresistive elements 22 and 24 are opposite to each other. Therefore, data with opposite polarities are written to the storage layers 22a and 24a of the magnetoresistive elements 22 and 24. Incidentally, in the seventh embodiment, a sign of a spin Hall angle of the conductive layer 10A is the same as a sign of a spin Hall angle of the conductive layer 10B.

The read operation is performed in the same manner as those according to the sixth embodiment.

Similarly to the first embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the seventh embodiment.

The write current may further be reduced in the seventh embodiment by applying a potential to the reference layers of the magnetoresistive element 22 and the magnetoresistive element 24 via the terminal 17 and the terminal 18 to control the interface magnetic anisotropy between the storage layers 22a and 24a and the nonmagnetic layers 22b and 24b.

The memory cells according to the first to fifth embodiments may also be reduced in cell size by stacking the magnetoresistive element 22 and the magnetoresistive element 24 as in the seventh embodiment.

#### Eighth Embodiment

A magnetic memory according to an eighth embodiment will be described with reference to FIG. 18. The magnetic memory according to the eighth embodiment includes at least one memory cell. FIG. 18 shows the memory cell.

The memory cell 1 according to the eighth embodiment has a configuration obtained by arranging the terminal 16 on the same side of the conductive layer 10 as the terminals (electrodes) 12 and 14 and the magnetoresistive elements 22 and 24 in the memory cell 1 according to the first embodiment shown in FIG. 5. Thus, the terminal 12 and the terminal 14 are separately disposed on the conductive layer 10, the terminal (electrode) 16 is disposed on the conductive layer 10 between the terminal 12 and the terminal 14, the magnetoresistive element 22 is disposed on the conductive layer 10 between the terminal 12 and the terminal 16, and the

18

magnetoresistive element 24 is disposed on the conductive layer 10 between the terminal 16 and the terminal 14.

The magnetoresistive element 22 has a multilayer structure including a storage layer 22a disposed on the conductive layer 10, a nonmagnetic layer 22b disposed on the storage layer 22a, and a reference layer 22c disposed on the nonmagnetic layer 22b. The magnetoresistive element 24 has a multilayer structure including a storage layer 24a disposed on the conductive layer 10, a nonmagnetic layer 24b disposed on the storage layer 24a, and a reference layer 24c disposed on the nonmagnetic layer 24b.

A sidewall insulating layer 40a is disposed between the terminal 12 and the magnetoresistive element 22, a sidewall insulating layer 40b is disposed between the magnetoresistive element 22 and the terminal 16, a sidewall insulating layer 40c is disposed between the terminal 16 and the magnetoresistive element 24, and a sidewall insulating layer 40d is disposed between the magnetoresistive element 24 and the terminal 14. Thus, the terminal 12 and the magnetoresistive element 22 are electrically insulated from each other by the sidewall insulating layer 40a, the magnetoresistive element 22 and the terminal 16 are electrically insulated from each other by the sidewall insulating layer 40b, the terminal 16 and the magnetoresistive element 24 are electrically insulated from each other by the sidewall insulating layer 40c, and the magnetoresistive element 24 and the terminal 14 are electrically insulated from each other by the sidewall insulating layer 40d.

The magnetoresistive elements 22 and 24 and the terminals 12, 14, and 16 of the memory cell 1 having the aforementioned configuration are formed in a self-aligning manner.

As indicated by arrows in FIG. 18, a write current  $I_w$  supplied from the terminal 16 to the conductive layer 10 passes through a lower portion of the conductive layer 10 under the magnetoresistive element 22, acts on the storage layer 22a of the magnetoresistive element 22, and goes through the terminal 12. On the other hand, the write current  $I_w$  supplied from the terminal 16 to a portion under the magnetoresistive element 24 acts on the storage layer 24a of the magnetoresistive element 24 with an opposite acting to that for the storage layer 22a, and goes through the terminal 14.

In this embodiment, the sidewall insulating layers 40a to 40d have a thickness (width) of several nm to about 10 nm. The sidewall insulating layer 40b, for example, electrically isolates an edge portion 42 of the lower surface of the terminal 16 on the magnetoresistive element 22 side from an edge portion 43 of the storage layer 22a of the magnetoresistive element 22 on the terminal 16 side with a very narrow width, and suppresses heat (power loss) caused by the current flowing between the edge portion 42 and the edge portion 43.

Part of the write current  $I_w$  also flows through the storage layers 22a and 24a. Therefore, the ratio of the width  $w_{SW}$  of each of the sidewall insulating layers 40a to 40d at the portion that is in contact with the conductive layer 10 to the thickness  $t$  of the conductive layer 10 has an influence on the amount of write current  $I_w$  flowing through the storage layers 22a and 24a.

As shown in FIG. 19, part of the write current  $I_w$  flowing from the terminal 16 into the conductive layer 10 and passing through a portion under the sidewall insulating layer 40c flows into the storage layer 24a, and then flows into the conductive layer 10 again and passes through a portion under the sidewall insulating layer 40d and flows into the terminal 14. The resistances of the terminal 16 and the

terminal **14** are considerably lower than the resistance of the conductive layer **10**. Therefore, the write current  $I_w$  concentrates to the edge portion of the terminal **16** as shown in FIG. **19**. The degree of concentration of the write current  $I_w$  increases if the distance  $w_{SW}$  between the storage layer **24a** and the terminal **16** and the terminal **14** is as thin as the thickness  $t$  of the conductive layer **10**. Such a concentration of the write current leads to a concentration of the current on the storage layer **24a** side to increase the current density on the storage layer side. This is equivalent to an increase in density of the write current, and thus enables the write current to be decreased. For example, if the thickness of the conductive layer **10** is about 5 nm, the current density may be increased by setting the thickness of each of the sidewall insulating layers **40a** to **40d** to be about 5 nm.

If the width  $w_{SW}$  of each of the sidewall insulating layers **40a** to **40d** is considerably thicker than the thickness  $d$  of the conductive layer **10** as shown in FIG. **20**, the increase in the current density of the write current becomes small, and does not have an influence on the reduction of the write current. (Manufacturing Method)

An example of a method of manufacturing a memory cell according to the eighth embodiment will be described with reference to FIGS. **21** to **29**.

First, a conductive layer **10** is formed on a substrate **300**, on which a CMOS device is disposed. A multilayer film **250** including a magnetic layer, a nonmagnetic layer, and a magnetic layer, which are to be included in magnetoresistive elements, is formed on the conductive layer **10**. Subsequently, a hard mask layer **260** and a hard mask layer **262** are deposited on the multilayer film **250** in this order, and patterned using a lithographic technique. As a result of the patterning, hard masks **262** and **260** are left on the multilayer film **250** above magnetoresistive elements that will be described later (FIG. **21**). The hard mask **260** is formed of a conducting material. The hard mask **262** is formed of a material having a higher etching rate than the material of the hard mask **260**.

Thereafter, the hard masks **262** are removed, and the multilayer film **250** is patterned by ion beam etching (IBE), using the hard masks **260**, to form magnetoresistive elements **22** and **24** under the hard masks **260** (FIG. **22**). A trench **264** is formed by the IBE through the multilayer film **250**. The surface of the conductive layer **10** is exposed on the bottom of the trench **264**.

An insulating layer **40** having a uniform thickness is then formed on side portions of the magnetoresistive elements **22** and **24**, using such a method as atomic layer deposition (ALD) (FIG. **23**).

The insulating layer **40** is etched by reactive ion etching (RIE) under a condition that etching particles with an anisotropy that is greater in a direction perpendicular to the substrate enter the insulating layer **40**. As a result, the insulating layer **40** is left on the side portions of the magnetoresistive elements **22** and **24** at which the etching particles do not hit strongly. Thus, the sidewall insulating layers **40a** to **40d** are formed. On the bottom of the trench **264**, the surface of the conductive layer **10** is exposed (FIG. **24**).

A film **270** of a good conducting material such as Cu or Ta is deposited to fill the trench **264** formed by the RIE, thereby forming an electrode film **270** (FIG. **25**).

The electrode film **270** is then smoothed by, for example, chemical mechanical polishing (CMP) to leave a metal film in the trench **264** (FIG. **26**).

An insulating layer **280** is formed to cover the top surface of the workpiece (FIG. **27**), and then vias **282** and **284**

communicating with the magnetoresistive elements **22** and **24** are formed through the insulating layer **280** (FIG. **28**). Finally, the vias **282** and **284** are filled with a conducting material, and the conducting material is smoothed to form terminals **17** and **18** connecting to the magnetoresistive elements **22** and **24** (see FIG. **5**). FIG. **29** is a cross-sectional view of the memory cell **1** thus formed.

According to this manufacturing method, the magnetoresistive elements **22** and **24** and the terminals **12**, **14**, and **16** are electrically insulated from each other by the sidewall insulating layers **40a** to **40d** having a predefined thickness. This structure has an advantage in that a constant write current may be supplied from the conductive layer **10** to the magnetoresistive elements **22** and **24** since the distance between the central position of the terminal **16** and the central position of the terminal **12** and the central position of the terminal **16** and the central position of the terminal **14** are the same (one pitch). Therefore, the range (window) of write current may be increased. This leads to an improvement in yield. Furthermore, the density of the write current may be increased at the edge portions of the magnetoresistive element by forming the sidewall insulating layers having a width (thickness) that is close to the thickness of the conductive layer **10**, which is controlled in the atom layer level. Thus, the write current may be reduced.

The conductive layer **10** may be over-etched during the RIE in the process shown in FIG. **24**. In this case, the terminals **12**, **14**, and **16** of the completed memory cell dig into the conductive layer **10**, as shown in FIG. **30**. The contact areas between the terminals **12**, **14**, and **16** and the conductive layer **10** can be increased by the structure in which the terminals **12**, **14**, and **16** dig into the conductive layer **10** as described above. Therefore, power loss caused by the contact resistance may be reduced. All of the terminals **12**, **14**, and **16** do not necessarily dig into the conductive layer **10** as shown in FIG. **30**. The power loss caused by the contact resistance can be reduced if one of the terminals digs into the conductive layer **10**.

As described above, similarly to the first embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the eighth embodiment.

#### Ninth Embodiment

A method of manufacturing a magnetic memory according to a ninth embodiment will be described with reference to FIGS. **31A** to **31F**. The magnetic memory according to the ninth embodiment includes at least three memory cells, each of which has the configuration shown in FIG. **29**.

First, as shown in FIG. **31A**, multilayer films **250<sub>1</sub>**, **250<sub>2</sub>**, and **250<sub>3</sub>** each including a first magnetic layer, a nonmagnetic layer, and a second magnetic layer to be included in magnetoresistive elements are formed in a stripe shape on a conductive layer (not shown). Spaces between the stripes are filled with insulating layers **252**, and the entire surface is smoothed. The direction along which the stripes extend is parallel to the cross section shown in FIG. **29**.

Subsequently, three grooves **264** are formed along a direction perpendicular to the direction along which the stripes extend, as shown in FIG. **31B**. The surface of the conductive layer **10** is exposed in regions at intersections of the multilayer films **250<sub>1</sub>** to **250<sub>3</sub>** and the grooves **264**. However, thin insulating layers **252a** are left in regions at intersections of the insulating layers **252** and the grooves **264** (FIG. **31B**).

Thereafter, sidewall insulating layers **40** are formed on both sides of each groove **264** and an electrode material is filled in the grooves **264** to form the terminals **12**, **16**, and **14** as shown in FIG. **31C**. As a result, the multilayer films **250<sub>1</sub>**, **250<sub>2</sub>**, and **250<sub>3</sub>** in portions between the terminal **12** and the terminal **16** become magnetoresistive elements **22<sub>1</sub>**, **22<sub>2</sub>**, and **22<sub>3</sub>**. Furthermore, the multilayer films **250<sub>1</sub>**, **250<sub>2</sub>**, and **250<sub>3</sub>** in portions between the terminal **16** and the terminal **14** become magnetoresistive elements **24<sub>1</sub>**, **24<sub>2</sub>**, and **24<sub>3</sub>**. Thus, memory cells are arranged in a direction along which the multilayer films **250<sub>1</sub>** to **250<sub>3</sub>** extend (FIG. **31C**).

An insulating layer **280** is then formed on the top surfaces of the memory cells as shown in FIG. **31D**. Subsequently, vias **282<sub>1</sub>**, **282<sub>2</sub>** and **282<sub>3</sub>** reaching the magnetoresistive elements **22<sub>1</sub>**, **22<sub>2</sub>** and **22<sub>3</sub>**, and vias **284<sub>1</sub>**, **284<sub>2</sub>** and **284<sub>3</sub>** reaching the magnetoresistive elements **24<sub>1</sub>**, **24<sub>2</sub>** and **24<sub>3</sub>** are formed through the insulating layer **280** (FIG. **31E**).

Thereafter, an electrode material **290** is deposited to fill the vias **282<sub>1</sub>**, **282<sub>2</sub>** and **282<sub>3</sub>** and the vias **284<sub>1</sub>**, **284<sub>2</sub>** and **284<sub>3</sub>** and patterned to have a stripe shape to form electrodes **290a** and **290b** for reading data from and writing data to the magnetoresistive elements **22<sub>1</sub>**, **22<sub>2</sub>** and **22<sub>3</sub>** and the magnetoresistive elements **24<sub>1</sub>**, **24<sub>2</sub>** and **24<sub>3</sub>**. As a result, memory cells are formed (FIG. **31F**). At this time, terminals **17<sub>1</sub>**, **17<sub>2</sub>** and **17<sub>3</sub>** are formed in the vias **282<sub>1</sub>**, **282<sub>2</sub>** and **282<sub>3</sub>** under the electrode **290a**, and terminals **18<sub>1</sub>**, **18<sub>2</sub>** and **18<sub>3</sub>** are formed in the vias **284<sub>1</sub>**, **284<sub>2</sub>** and **284<sub>3</sub>** under the electrode **290b**.

As shown in FIG. **32**, a write circuit **110** is connected to the electrodes **12**, **14**, and **16**, and a readout circuit **120** is connected to the electrodes **290a** and **290b** of the magnetic memory manufactured in the aforementioned method. The write circuit **110** and the readout circuit **120** are included in the control circuit **100** shown in FIG. **1**. The readout circuit **120** is also used to apply a bias voltage to the magnetoresistive elements **22<sub>1</sub>** to **22<sub>3</sub>** and the magnetoresistive elements **24<sub>1</sub>** to **24<sub>3</sub>** in a write operation.

Similarly to the eighth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the ninth embodiment.

#### Tenth Embodiment

A magnetic memory according to a tenth embodiment will be described with reference to FIGS. **33** to **37**. The magnetic memory according to the tenth embodiment includes at least one memory cell. FIG. **33** shows the memory cell. The memory cell has a configuration obtained by replacing the storage layers **22a** and **24a** and the reference layers **22c** and **24c** of the magnetoresistive elements **22** and **24** included in the memory cell **1** according to the eighth embodiment shown in FIG. **18** with layers with perpendicular magnetization that is parallel to the stacking direction of the magnetoresistive elements **22** and **24**, and replacing the electrodes **12**, **14**, and **16** with electrodes **12a**, **14a**, and **16a** including metal magnetic layers. The electrodes **12a**, **14a**, and **16a** have a magnetization that is parallel to a direction along which the conductive layer **10** extends, for example a direction from left to right in the drawings.

With this configuration, a biased magnetic field is generated at the electrodes **12a**, **14a**, and **16a**, which assists the switching of the magnetizations of the storage layers **22a** and **24a**, the magnetizations being in a direction perpendicular to the stacking direction of the magnetoresistive elements **22** and **24**.

(First Modification)

The assisting magnetic field may be applied to the storage layers **22a** and **24a** not only in the direction along which the conductive layer **10** extends but also in a direction crossing the direction along which the conductive layer **10** extends, as in a first modification shown in FIG. **34**.

(Second Modification)

The electrode **16a** disposed in the center may be formed of a magnetic metal, and the electrodes **12** and **14** disposed on the right and left sides of the electrode **16a** may be formed of a nonmagnetic metal, as in a second modification shown in FIG. **35**.

(Third Modification)

The electrodes may be formed as in a third modification shown in FIG. **36**. The third modification has a configuration obtained by disposing nonmagnetic metal layers **41a**, **41b**, and **41c** on the outer surfaces of the electrodes **12**, **14**, and **16** in the first modification shown in FIG. **33**. With this configuration, the electrodes **12a**, **14a**, and **16a** may have a good hard magnetic property.

(Fourth Modification)

In the tenth embodiment and the first to third modifications of the tenth embodiment, the biased magnetic field, i.e., the magnetizations of the electrodes **12a**, **14a**, and **16a**, is in an in-plane direction. However, the biased magnetic field may be in a perpendicular direction as in a fourth modification shown in FIG. **37**. A memory cell **1** according to the fourth modification has a configuration obtained by replacing the electrode **16a** of the memory cell **1** according to the second modification shown in FIG. **35** with an electrode **16b**. The electrode **16b** includes a nonmagnetic metal layer **16b1** and a metal magnetic layer **16b2**. The nonmagnetic metal layer **16b1** has a bottom that is in contact with the conductive layer **10**, and side surfaces that are in contact with the sidewall insulating layers **41b** and **41c**. The metal magnetic layer **16b2** is disposed in the nonmagnetic metal layer **16b1**, and has a perpendicular magnetization. The metal magnetic layer **16b2** is located in the nonmagnetic metal layer **16b1** so as to be higher than the storage layers **22a** and **24a** of the magnetoresistive elements **22** and **24**.

If the biased magnetic field acts as a perpendicular magnetization, the biased magnetic field may effectively switch the magnetization of the storage layer if it is disposed in the electrode **16b**.

If the biased magnetic field acts as an in-plane magnetization, the biased magnetic field may effectively switch the magnetization of the storage layer if the magnetic metal layers are disposed on both sides of the magnetoresistive element **22** and the magnetoresistive element **24**.

As described above, similarly to the eighth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the tenth embodiment and the modifications of the tenth embodiment.

#### Eleventh Embodiment

A magnetic memory according to an eleventh embodiment will be described with reference to FIG. **38**. The magnetic memory according to the eleventh embodiment includes at least two memory cells **1<sub>1</sub>** and **1<sub>2</sub>**. FIG. **38** is a cross-sectional view of the memory cells **1<sub>1</sub>** and **1<sub>2</sub>**. The memory cells **1<sub>1</sub>** and **1<sub>2</sub>** each have the same configuration as the memory cell **1** according to the eighth embodiment shown in FIG. **18**, and disposed on the same conductive layer **10**. The right side electrode of the memory cell **1<sub>1</sub>** is

shared by the electrode of the memory cell  $1_2$  and serves as the left side electrode of the memory cell  $1_2$ .

Thus, the memory cell  $1_1$  includes electrodes  $12_1$ ,  $14_1$ , and  $16_1$  disposed on the conductive layer  $10$ , and magnetoresistive elements  $22_1$  and  $24_1$  disposed on the conductive layer  $10$ . The electrode  $16_1$  is disposed in a region of the conductive layer  $10$  between the electrode  $12_1$  and the electrode  $14_1$ . The magnetoresistive element  $22_1$  is disposed in a region of the conductive layer  $10$  between the electrode  $12_1$  and the electrode  $16_1$ , and the magnetoresistive element  $24_1$  is disposed in a region of the conductive layer  $10$  between the electrode  $16_1$  and the electrode  $14_1$ . A sidewall insulating layer  $40a$  is disposed between the electrode  $12_1$  and the magnetoresistive element  $22_1$ , and a sidewall insulating layer  $40b$  is disposed between the magnetoresistive element  $22_1$  and the electrode  $16_1$ . A sidewall insulating layer  $40c$  is disposed between the electrode  $16_1$  and the magnetoresistive element  $24_1$ , and a sidewall insulating layer  $40d$  is disposed between the magnetoresistive element  $24_1$  and the electrode  $14_1$ .

The memory cell  $1_2$  includes electrodes  $14_2$  and  $16_2$  disposed on the conductive layer  $10$ , and magnetoresistive elements  $22_2$  and  $24_2$  disposed on the conductive layer  $10$ . The electrode  $16_2$  is disposed in a region of the conductive layer  $10$  between the electrode  $14_1$  and the electrode  $14_2$ . The magnetoresistive element  $22_2$  is disposed in a region of the conductive layer  $10$  between the electrode  $14_1$  and the electrode  $16_2$ , and the magnetoresistive element  $24_2$  is disposed in a region of the conductive layer  $10$  between the electrode  $16_2$  and the electrode  $14_2$ . A sidewall insulating layer  $40e$  is disposed between the electrode  $14_1$  and the magnetoresistive element  $22_2$ , and a sidewall insulating layer  $40f$  is disposed between the magnetoresistive element  $22_2$  and the electrode  $16_2$ . A sidewall insulating layer  $40g$  is disposed between the electrode  $16_2$  and the magnetoresistive element  $24_2$ , and a sidewall insulating layer  $40h$  is disposed between the magnetoresistive element  $24_2$  and the electrode  $14_2$ .

Thus, the memory cell  $1_1$  and the memory cell  $1_2$  are disposed on the same conductive layer  $10$ , and share the electrode  $14_1$ .

In the magnetic memory according to the eleventh embodiment, information is recorded in the magnetoresistive element  $22_1$  and the magnetoresistive element  $24_1$  by causing a write current  $Iw1$  to flow from the electrode  $16_1$  to electrode  $12_1$  and from the electrode  $16_1$  to the electrode  $14_1$  via the conductive layer  $10$ . On the other hand, information is recorded in the magnetoresistive element  $22_2$  and the magnetoresistive element  $24_2$  by causing a write current  $Iw2$  to flow from the electrode  $16_2$  to the electrode  $14_1$  and from the electrode  $16_2$  to the electrode  $14_2$  via the conductive layer  $10$ . The above configuration enables the four magnetoresistive elements  $22_1$ ,  $24_1$ ,  $22_2$ , and  $24_2$  to be disposed among the five electrodes  $12_1$ ,  $16_1$ ,  $14_1$ ,  $16_2$ , and  $14_2$ . This leads to a reduction in length by one electrode as compared to the magnetic memory including four independent magnetoresistive elements that are simply arranged.

Similarly to the eighth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the eleventh embodiment.

#### Twelfth Embodiment

A method of manufacturing a magnetic memory according to a twelfth embodiment will be described with reference to FIGS. 39 to 45. FIGS. 39 to 45 are cross-sectional views

illustrating the method of manufacturing the magnetic memory according to the twelfth embodiment. The method according to this embodiment is for manufacturing the magnetic memory shown in FIG. 1, in which the terminal  $16$  is disposed on the lower surface of the conductive layer  $10$ , and the terminals  $12$  and  $14$  and the magnetoresistive elements  $22$  and  $24$  are disposed on the top surface of the conductive layer  $10$ .

First, a transistor  $410$  is formed on a semiconductor layer  $400$  as shown in FIG. 39. The transistor  $410$  has a source  $410a$ , and a drain  $410b$  that are separately disposed on the semiconductor layer  $400$ , and a gate  $410d$  disposed above a region (channel)  $410c$  of the semiconductor layer  $400$  between the source  $410a$  and the drain  $410b$ . An insulating film  $420$  is disposed on the transistor  $410$ . A terminal  $424$  connecting to the drain  $410b$  is formed through the insulating film  $420$ . A terminal  $422$  connecting to the source  $410a$  is formed on the source  $410a$  in the insulating film  $420$ .

An insulating film  $430$  is disposed on the insulating film  $420$ , through which a terminal  $432$  connecting to the terminal  $424$  is formed. The terminal  $432$  may be formed of the same material as the terminal  $424$ . If, however, a magnetic layer  $19b$  is formed in the terminal  $432$  for generating a biased magnetic field as shown in FIGS. 15A to 15C, a different material, which is a hard magnetic material, is used.

Subsequently, as shown in FIG. 40, a conductive layer  $440$  is formed to cover the insulating film  $430$  and the terminal  $432$ , and a magnetoresistive film  $450$  is disposed on the conductive layer  $440$ . The magnetoresistive film  $450$  is a multilayer film including a magnetic layer to become a storage layer disposed on the conductive layer  $440$ , a non-magnetic layer to become a tunnel barrier disposed on the magnetic layer, and a magnetic layer to become a reference layer disposed on the nonmagnetic layer. For simplification of explanation, the insulating film  $420$  and the terminal  $424$  and the layers that are disposed in and under the insulating film  $420$  and the terminal  $424$  are omitted in FIG. 40 and FIGS. 41 to 45, which will be described later.

Thereafter, as shown in FIG. 41, the magnetoresistive film  $450$  is patterned to form magnetoresistive elements  $452$  and  $454$ .

An insulating film  $460$  is then deposited to cover the magnetoresistive elements  $452$  and  $454$  as shown in FIG. 42. Lead electrodes  $462$  and  $464$  are formed through the insulating film  $460$  by forming two openings reaching the conductive layer  $440$  in the insulating film  $460$  by a lithographic technique, and filling the openings with a metal material. The magnetoresistive elements  $452$  and  $454$  are disposed between the lead electrode  $462$  and the lead electrode  $464$  (FIG. 43).

Thereafter an insulating film  $470$  is formed to cover the lead electrodes  $462$  and  $464$  and the magnetoresistive elements  $452$  and  $454$  as shown in FIG. 44. Four openings are formed through the insulating film  $470$  by a lithographic technique, the openings reaching the lead electrode  $462$ , the magnetoresistive element  $452$ , the magnetoresistive element  $454$ , and the lead electrode  $464$ . The openings are filled with a metal material to form terminals  $472$ ,  $474$ ,  $476$ , and  $478$  connecting to the lead electrode  $462$ , the magnetoresistive element  $452$ , the magnetoresistive element  $454$ , and the lead electrode  $464$ . As a result, the magnetic memory according to the first embodiment shown in FIG. 1 is completed, as shown in FIG. 45.

Similarly to the first embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed by the magnetic memory manufactured according to the twelfth embodiment.

FIG. 46 is a circuit diagram illustrating a magnetic memory according to a thirteenth embodiment. The magnetic memory according to the thirteenth embodiment includes a plurality of memory cells  $1_1, 1_2, \dots$ , selection circuits 500 and 510, a write circuit 520, a readout circuit 530, and a sense amplifier 540. The memory cells  $1_1, 1_2, \dots$  are arranged in one direction (vertical direction) in FIG. 46, but may be arranged in a horizontal direction or in a matrix form as will be described as a modification later.

Each of the memory cells  $1_1$  and  $1_2$  includes a conductive layer 10, terminals 12 and 14 separately disposed on the conductive layer 10, a terminal 16 disposed in a region of the conductive layer 10 between the terminal 12 and the terminal 14, a magnetoresistive element 22 disposed in a region of the conductive layer 10 between the terminal 12 and the terminal 16, and a magnetoresistive element 24 disposed in a region of the conductive layer 10 between the terminal 16 and the terminal 14.

Each of the magnetoresistive elements 22 and 24 includes a storage layer (not shown) disposed on the conductive layer 10, a nonmagnetic layer (not shown) disposed on the storage layer, and a reference layer (not shown) disposed on the nonmagnetic layer. The reference layer of the magnetoresistive element 22 is electrically connected to a terminal 17, and the reference layer of the magnetoresistive element 24 is electrically connected to a terminal 18.

One (terminal) of a source and a drain of a transistor 31 is connected to the terminal 12, and the other (terminal) is connected to a first bit line BLL. One (terminal) of a source and a drain of a transistor 32 is connected to the terminal 14, and the other (terminal) is connected to a second bit line BLR. One (terminal) of a source and a drain of a transistor 34 is connected to the terminal 17, and the other (terminal) is connected to the first bit line BLL. One (terminal) of a source and a drain of a transistor 35 is connected to the terminal 18, and the other (terminal) is connected to the second bit line BLR.

A gate (control terminal) of each of the transistors 31 and 32 is connected to a write word line  $WWL_i$ , a gate (control terminal) of each of the transistors 34 and 35 is connected to a read word line  $RWL_i$ , and the terminal 16 is connected to a source line SL in each memory cell  $1_i$  ( $i=1, 2, \dots$ ).

The write word lines  $WWL_i$  ( $i=1, 2, \dots$ ) and the read word lines  $RWL_i$  ( $i=1, 2, \dots$ ) are connected to a word line selection circuit that is not shown.

The first bit line BLL, the second bit line BLR, and the source line SL are connected to the selection circuits 500 and 510. They are connected to the write circuit 520 via the selection circuit 500 in a write operation, and are connected to the readout circuit 540 via the selection circuit 500 and to the sense amplifier 540 via the selection circuit 510 in a read operation. Although the selection circuits 500 and 510, the write circuit 520, the readout circuit 530, and the sense amplifier 540 are disposed on an upper portion or a lower portion in FIG. 46, they may be disposed together on one side or disposed separately on both sides in a physical layout on a chip.

Operations of the magnetic memory according to the thirteenth embodiment will then be described with reference to FIGS. 47 and 48.

(Write Operation)

FIG. 47 shows a write operation of the magnetic memory according to the thirteenth embodiment. In the magnetic memory according to the thirteenth embodiment, no assist voltage is applied to the terminals 17 and 18 of the magne-

toresistive elements 22 and 24 in a write operation. FIG. 47 shows voltages that are applied when a write operation is performed on a memory cell  $1_1$ . In this case, data "0" is written to one of the magnetoresistive element 22 and the magnetoresistive element 24, and data "1" is written to the other in the memory cell  $1_1$ .

The selection circuit 500 connects the first bit line BLL, the second bit line BLR, and the source line SL to the write circuit 520 to write data. Subsequently, the selection circuit 500 applies a write selection potential VDD (VGW) to the write word line  $WWL_1$ , and a potential 0 V to the write word line  $WWL_2$  and the read word lines  $RWL_1$  and  $RWL_2$ . As a result, the transistors 31 and 32 are turned on and the transistors 34 and 35 are turned off in the memory cell  $1_1$ . In the other memory cell  $1_2$ , the transistors 31, 32, 34, and 35 are turned off.

In this state, electric currents are caused to flow symmetrically in the opposite directions through the conductive layer 10 of the selected memory cell  $1_1$  in order to write data "0" to the magnetoresistive element 22 and data "1" to the magnetoresistive element 24 of the selected memory cell  $1_1$ . For example, a write voltage  $V_{write}$  is applied to the first bit line BLL and the second bit line BLR, and a voltage 0 V is applied to the source line SL. As a result, the write current  $I_w$  for writing data to the magnetoresistive element 22 flows from the first bit line BLL to the source line SL via the transistor 31, the terminal 12, the conductive layer 10, and the terminal 16. On the other hand, the write current  $I_w$  for writing data to the magnetoresistive element 24 flows from the second bit line BLR to the source SL via the transistor 32, the terminal 14, the conductive layer 10, and the terminal 16. Thus, the write currents  $I_w$  flow along solid line arrows in FIG. 47.

If data are written in an opposite manner, for example, if data "1" is written to the magnetoresistive element 22 and data "0" is written to the magnetoresistive element 24 in the selected memory cell  $1_1$ , 0 V is applied to the first bit line BLL and the second bit line BLR and the write voltage  $V_{write}$  is applied to the source line SL to have write currents with opposite polarities. As a result, a write current  $I_w'$  to write data to the magnetoresistive element 22 flows from the source line SL to the first bit line BLL via the terminal 16, the conductive layer 10, the terminal 12, and the transistor 31. On the other hand, a write current  $I_w'$  to write data to the magnetoresistive element 24 flows from the source line SL to the second bit line BLR via the terminal 16, the conductive layer 10, the terminal 14, and the transistor 32. Thus, the write currents  $I_w'$  flow along broken line arrows in FIG. 47. (Read Operation)

FIG. 48 illustrates a read operation of the magnetic memory according to the thirteenth embodiment. FIG. 48 shows voltages that are applied when a read operation is performed on the memory cell  $1_1$ . In the thirteenth embodiment, the sense amplifier 540 reads a differential signal.

In order to read data, the selection circuits 500 and 510 connect the first bit line BLL, the second bit line BLR, and the source line SL to the readout circuit 530 and the sense amplifier 540. Thus, the sense amplifier 540 is connected to the first bit line BLL and the second bit line BLR via the selection circuit 510.

The first bit line BLL and the second bit line BLR are discharged and equalized in advance.

Subsequently, a read selection potential VGR is applied to the read word line  $RWL_1$ , and a potential 0 V is applied to the read word line  $RWL_2$  and the write word lines  $WWL_1$  and  $WWL_2$ . The read selection potential VGR may be equal to the write selection potential VGW. As a result, the

transistors **34** and **35** are turned on and the transistors **31** and **32** are turned off in the memory cell  $1_1$ . In the memory cell  $1_2$ , the transistors **31**, **32**, **34**, and **35** are turned off. This means that the selected memory cell  $1_1$  is turned on, and when the read voltage  $V_{read}$  is applied to the source line SL in this state, the charging rate differs between the first bit line BLL and the second bit line BLR due to the difference in resistance value between the magnetoresistive elements **22** and **24**. As a result, a potential difference is caused between the first bit line BLL and the second bit line BLR. Then, the sense amplifier **540** determines whether the data stored in the selected memory cell  $1_1$  is "0" or "1." Although the read operation is performed based on a potential difference in this embodiment, a current difference may also be used.

(Modification)

FIG. **49** illustrates a magnetic memory according to a modification of the thirteenth embodiment. The magnetic memory according to the modification includes a plurality of memory cells that are arranged in a matrix form. Each memory cell  $1_{ij}$  ( $i, j=1, 2, \dots$ ) has the same configuration as the memory cell shown in FIG. **46**.

In each memory cell  $1_{ij}$  ( $i, j=1, 2, \dots$ ), one of the source and the drain of the transistor **31** is electrically connected to the terminal **12**, the other is electrically connected to the first bit line  $BLL_j$ , and the gate is connected to the write word line  $WWL_i$ . One of the source and the drain of the transistor **32** is electrically connected to the terminal **14**, the other is electrically connected to the second bit line  $BLR_j$ , and the gate is connected to the write word line  $WWL_i$ . One of the source and the drain of the transistor **34** is electrically connected to the terminal **17**, the other is electrically connected to the first bit line  $BLL_j$ , and the gate is connected to the read word line  $RWL_i$ . One of the source and the drain of the transistor **35** is electrically connected to the terminal **18**, the other is connected to the second bit line  $BLR_j$ , and the gate is connected to the read word line  $RWL_i$ .

Data can be written and read in the same manner as in the thirteenth embodiment in the modification having the above configuration.

Data of one bit is stored in each memory cell of the thirteenth embodiment and the modification of the thirteenth embodiment.

Energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the thirteenth embodiment and the modification of the thirteenth embodiment.

#### Fourteenth Embodiment

FIG. **50** illustrates a magnetic memory according to a fourteenth embodiment. The magnetic memory according to the fourteenth embodiment differs from the magnetic memory according to the thirteenth embodiment shown in FIG. **46** in that the first bit line BLL and the second bit line BLR are replaced with a first write bit line WBLL, a second write bit line WBLR, a first read bit line RBLL, and a second read bit line RBLL, and thus the connections of the transistors **31**, **32**, **34**, and **35** are changed.

In each of the memory cells  $1_1$  and  $1_2$ , one of the source and the drain of the transistor **31** is electrically connected to the terminal **12**, and the other is electrically connected to the first write bit line WBLL. One of the source and the drain of the transistor **32** is connected to the terminal **14**, and the other is electrically connected to the second write bit line WBLR. One of the source and the drain of the transistor **34** is electrically connected to the terminal **17**, and the other is electrically connected to the first read bit line RBLL. One of

the source and the drain of the transistor **35** is electrically connected to the terminal **18**, and the other is electrically connected to the second read bit line RBLL.

The gates of the transistors **31** and **32** in each memory cell  $1_i$  ( $i=1, 2, \dots$ ) are electrically connected to the write word line  $WWL_i$ , and the gates of the transistors **34** and **35** are electrically connected to the read word line  $RWL_i$  as in the thirteenth embodiment.

In the magnetic memory according to the fourteenth embodiment, an assist voltage is applied to the terminals **17** and **18** of the magnetoresistive elements **22** and **24** in a write operation. In the write operation, not only the transistors **31** and **32** but also the transistors **34** and **35** of the selected memory cell are turned on, and the assist voltage is applied through the first read bit line RBLL and the second read bit line RBLL. Other processes in the write operation are the same as those in the thirteenth embodiment.

In a read operation, the transistors **31** and **32** are turned off, the transistors **34** and **35** in the selected memory cell are turned on, and the same processes as those in the thirteenth embodiment are performed.

In the fourteenth embodiment, the assist voltages are applied, in the write operation, to the terminals **17** and **18** that are electrically connected to the reference layers of the magnetoresistive elements. This enables the magnetization switching of the storage layers of the magnetoresistive elements to be performed more easily.

Similarly to the thirteenth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the fourteenth embodiment.

#### Fifteenth Embodiment

FIG. **51** illustrates a magnetic memory according to a fifteenth embodiment. The magnetic memory according to the fifteenth embodiment has a configuration obtained by removing the transistor **32** and electrically connecting the terminal **14** to one of the source and the drain of the transistor **31** that is electrically connected to the terminal **12** in the magnetic memory according to the thirteenth embodiment shown in FIG. **46**.

A write operation is performed by causing a write current to flow between the first bit line BLL and the source line SL via the transistor **31** and the terminals **12**, **14**, and **16**. A read operation is performed in the same manner as the read operation for the magnetic memory according to the thirteenth embodiment.

In the magnetic memory according to the fifteenth embodiment, a memory cell includes two magnetoresistive elements **22** and **24** and three transistors **31**, **34**, and **35**, and data of one bit is stored in one memory cell.

Similarly to the thirteenth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the fifteenth embodiment.

#### Sixteenth Embodiment

FIG. **52** illustrates a magnetic memory according to a sixteenth embodiment. The magnetic memory according to the sixteenth embodiment has a configuration obtained by replacing the first bit line BLL with a write bit line WBL and a first read bit line RBLL and replacing the second bit line BLR with a second read bit line RBLL in the magnetic memory according to the fifteenth embodiment shown in FIG. **51**.



In each memory cell  $1_i$  ( $i=1, 2, \dots$ ), one of the source and the drain of the transistor **31** is connected to the terminal **12**, the other is electrically connected to the write bit line WBL, and the gate is electrically connected to the write word line WWL<sub>*i*</sub>. One of the source and the drain of the transistor **34** is electrically connected to the terminal **17**, the other is electrically connected to the first read bit line RBLL, and the gate is electrically connected to the read word line RWL<sub>*i*</sub>. One of the source and the drain of the transistor **35** is electrically connected to the terminal **18**, the other is electrically connected to the second read bit line RBLR, and the gate is electrically connected to the read word line RWL<sub>*i*</sub>.

A write operation is performed by causing a write current to flow between the write bit line WBL and the source line SL via the transistor **31** and the terminals **12**, **14**, **16**, as in the magnetic memory according to the fourteenth embodiment shown in FIG. **51**. A read operation is performed in the same manner as the read operation for the magnetic memory according to the thirteenth embodiment.

Similarly to the fifteenth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the sixteenth embodiment.

#### Seventeenth Embodiment

A magnetic memory according to a seventeenth embodiment will be described with reference to FIGS. **53** to **55**. FIG. **53** is a circuit diagram illustrating a magnetic memory according to the seventeenth embodiment, FIG. **54** is a circuit diagram for explaining a write operation of the magnetic memory according to the seventeenth embodiment, and FIG. **55** is a circuit diagram for explaining a read operation of the magnetic memory according to the seventeenth embodiment.

The magnetic memory according to the seventeenth embodiment has a configuration obtained by replacing the sense amplifier **540** with sense amplifiers **540a** and **540b** in the thirteenth embodiment shown in FIG. **46**. Each memory cell  $1_i$  ( $i=1, 2, \dots$ ) has the same configuration as the memory cell of the thirteenth embodiment shown in FIG. **46**, but the magnetoresistive elements **22** and **24** independently store data. Thus, each memory cell  $1_i$  ( $i=1, 2, \dots$ ) stores data of two bits. Therefore, the differential amplifying method used in the thirteenth embodiment cannot be used, and for this reason the two sense amplifiers **540a** and **540b** are used. The sense amplifier **540a** is electrically connected to the first bit line BLL via the selection circuit **510**, and the sense amplifier **540b** is electrically connected to the second bit line BLR via the selection circuit **510**. Each of the sense amplifiers **540a** and **540b** compares the potential of the corresponding bit line with a reference potential, and determines whether the data outputted to the corresponding bit line is "0" or "1." (Write Operation)

A write operation will then be described with reference to FIG. **54**. FIG. **54** is a circuit diagram illustrating a write operation to write data to the memory cell  $1_1$ .

Different data are written to the magnetoresistive elements **22** and **24** of the memory cell  $1_1$  in the same manner as the write operation to write data in the thirteenth embodiment shown in FIG. **47**.

In the write operation, the selection circuit **500** connects the first bit line BLL, the second bit line BLR, and the source line SL to the write circuit **520**. Subsequently, a write selection potential VGW is applied to the write word line WWL<sub>1</sub>, and a potential 0 V is applied to the write word line WWL<sub>2</sub> and the read word lines RWL<sub>1</sub> and RWL<sub>2</sub>. As a

result, the transistors **31** and **32** are turned on and the transistors **34** and **35** are turned off in the memory cell  $1_1$ . The transistors **31**, **32**, **34**, and **35** are turned off in the other memory cell  $1_2$ .

In order to write data "0" to the magnetoresistive element **22** and data "1" to the magnetoresistive element **24** of the selected memory cell  $1_1$ , electric currents are caused to flow in opposite directions through the conductive layer **10** of the selected memory cell  $1_1$ . For example, a write voltage  $V_{write}$  is applied to the first bit line BLL and the second bit line BLR, and a voltage 0 V is applied to the source line SL. As a result, the write current Iw1 for the magnetoresistive element **22** flows from the first bit line BLL to the source line SL via the transistor **31**, the terminal **12**, the conductive layer **10**, and the terminal **16**. On the other hand, the write current Iw1 for the magnetoresistive element **24** flows from the second bit line BLR to the source SL via the transistor **32**, the terminal **14**, the conductive layer **10**, and the terminal **16**. Thus, the write currents Iw1 flow along solid line arrows in FIG. **54**.

If data is written in an opposite manner, and for example, if data "1" is written to the magnetoresistive element **22** and data "0" is written to the magnetoresistive element **24** in the selected memory cell  $1_1$ , 0 V is applied to the first bit line BLL and the second bit line BLR, and the write voltage  $V_{write}$  is applied to the source line SL to have write currents with opposite polarities. As a result, a write current Iw1' for the magnetoresistive element **22** flows from the source line SL to the first bit line BLL via the terminal **16**, the conductive layer **10**, the terminal **12**, and the transistor **31**. On the other hand, a write current Iw1' for the magnetoresistive element **24** flows from the source line SL to the second bit line BLR via the terminal **16**, the conductive layer **10**, the terminal **14**, and the transistor **32**. Thus, the write currents Iw1' flow along broken line arrows in FIG. **54**.

If the same data is written to the magnetoresistive elements **22** and **24** in the memory cell  $1_1$ , a write operation is performed in the following manner.

The selection circuit **500** connects the first bit line BLL and the second bit line BLR to the write circuit **520**. The source line SL is brought into a floating state. Subsequently, a write selection potential VGW is applied to the write word line WWL<sub>*i*</sub>, and a potential 0 V is applied to the write word line WWL<sub>2</sub> and the read word lines RWL<sub>1</sub> and RWL<sub>2</sub>. As a result, the transistors **31** and **32** are turned on and the transistors **34** and **35** are turned off in the memory cell  $1_1$ . In the other memory cell  $1_2$ , the transistors **31**, **32**, **34**, and **35** are turned off.

In this state, an electric current is caused to flow in one direction through the conductive layer **10** of the selected memory cell  $1_1$  to write data "0," for example, to the magnetoresistive elements **22** and **24** of the selected memory cell  $1_1$ . For example, a write voltage  $V_{write}$  is applied to the first bit line BLL, and a voltage 0 V is applied to the second bit line BLR. As a result, a write current Iw2 for writing data to the magnetoresistive elements **22** and **24** flows from the first bit line BLL to the second bit line BLR via the transistor **31**, the terminal **12**, the conductive layer **10**, the terminal **14**, and the transistor **32**. Thus, the write current Iw2 flows along the solid line arrow shown in FIG. **54**.

If the other data is written, for example if data "1" is written to the magnetoresistive elements **22** and **24** in the selected memory cell  $1_1$ , 0 V is applied to the first bit line BLL and the write voltage  $V_{write}$  is applied to the second bit line BLR to have a write current with an opposite polarity. As a result, a write current Iw2' for writing data to the magnetoresistive elements **22** and **24** flows from the second

## 31

bit line BLR to the first bit line BLL via the transistor 32, the terminal 14, the conductive layer 10, the terminal 12, and the transistor 31. Thus, the write current  $I_{w2'}$  flows along a broken line arrow shown in FIG. 54.

As described above, not only different data (0, 1), (1, 0) but also the same data (0, 0), (1, 1) may be written to the magnetoresistive elements 22 and 24 of each memory cell  $1_i$  ( $i=1, 2, \dots$ ). This makes it possible to write all of the required data patterns to the magnetoresistive elements 22 and 24.

(Read Operation)

A read operation will then be described with reference to FIG. 55. FIG. 55 is a circuit diagram illustrating an operation to read data from the memory cell  $1_1$ .

The selection circuit 500 connects the first bit line BLL, the second bit line BLR, and the source line SL to the readout circuit 530, and the selection circuit 510 connects the sense amplifier 540a to the first bit line BLL, and the sense amplifier 540b to the second bit line BLR.

Subsequently, the selection circuit 500 applies 0 V to the write word line  $WWL_1$  connected to the selected memory cell  $1_1$  to turn off the transistors 31 and 32, and a read selection potential VGR to the read word line  $RWL_1$  connected to the selected memory cell  $1_1$  to turn on the transistors 34 and 35.

If data is read from the magnetoresistive element 22 in this state, for example, a read voltage  $V_{read}$  is applied to the source line SL, and 0 V is applied to the first bit line BLL. When the signal on the first bit line BLL is saturated, the sense amplifier 540a compares the potential of the first bit line BLL and a reference potential, and determines whether the data stored in the magnetoresistive element 22 is "0" or "1" on the basis of the comparison result.

On the other hand, if data is read from the magnetoresistive element 24, for example, the second bit line BLR is discharged, and then a read voltage  $V_{read}$  is applied to the source line SL. When the signal on the second bit line BLR is saturated, the sense amplifier 540b compares the potential of the second bit line BLR and the reference potential, and determines whether the data stored in the magnetoresistive element 24 is "0" or "1" on the basis of the comparison result.

Each memory cell of the magnetic memory according to the seventeenth embodiment stores two-bit data. Therefore, the occupied area per one bit is a half of that in the magnetic memory according to the thirteenth embodiment. This improves the density.

Similarly to the thirteenth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the seventeenth embodiment.

## Eighteenth Embodiment

A magnetic memory according to an eighteenth embodiment will be described with reference to FIGS. 56 to 58. FIG. 56 is a top view of the magnetic memory according to the eighteenth embodiment, FIG. 57 is a cross-sectional view taken along line A-A of FIG. 56, and FIG. 58 is a cross-sectional view taken along line B-B of FIG. 56.

The magnetic memory according to the eighteenth embodiment includes at least four memory cells  $1_{11}$  to  $1_{22}$ , which are arranged in a matrix form, each memory cell having the same configuration as the memory cell according to the thirteenth embodiment shown in FIG. 46. Thus, each memory cell includes a conductive layer 10, magnetoresistive elements 22 and 24 disposed on the conductive layer 10,

## 32

and four transistors 31, 32, 34, and 35. FIG. 56 can be understood to be a top view of the magnetic memory according to the thirteenth embodiment shown in FIG. 49.

As can be understood from FIGS. 57 and 58, each of the transistors 31, 32, 34, and 35 are a vertical transistor. The gates of the transistors 31 and 32 in the memory cells  $1_{i1}$  and  $1_{i2}$  ( $i=1, 2$ ) form a write word line  $WWL_i$  (see FIG. 58), and the gates of the transistors 34 and 35 form a read word line  $RWL_i$  (see FIG. 57).

A first bit line  $BLL_1$  and a second bit line  $BLR_1$  connected to the memory cell  $1_{i1}$  ( $i=1, 2$ ) are disposed below the memory cell  $1_{i1}$  ( $i=1, 2$ ), and a first bit line  $BLL_2$  and a second bit line  $BLR_2$  connected to the memory cell  $1_{i2}$  ( $i=1, 2$ ) are disposed on the same level as the first bit line  $BLL_1$  and the second bit line  $BLR_1$  (FIGS. 57 and 58). The terminals 17 and 18 are disposed on an upper layer. The conductive layer 10 is disposed above the first bit lines  $BLL_1$  and  $BLL_2$  and the second bit lines  $BLR_1$  and  $BLR_2$ , and the terminals 17 and 18 are disposed above the conductive layer 10.

In the memory cell  $1_{i1}$  ( $i=1, 2$ ), one of the source and the drain of the transistor 31 is electrically connected to the first bit line  $BLL_1$ , and the other is electrically connected to the terminal 12. One of the source and the drain of the transistor 32 is electrically connected to the second bit line  $BLR_1$ , and the other is electrically connected to the terminal 14. One of the source and the drain of the transistor 34 is electrically connected to the first bit line  $BLL_1$ , and the other is electrically connected to the terminal 17 via a plug 601. One of the source and the drain of the transistor 35 is electrically connected to the second bit line  $BLR_1$ , and the other is electrically connected to the terminal 18 via a plug 602.

In the memory cell  $1_{i2}$  ( $i=1, 2$ ), one of the source and the drain of the transistor 32 is electrically connected to the first bit line  $BLL_2$ , and the other is electrically connected to the terminal 12. One of the source and the drain of the transistor 33 is electrically connected to the second bit line  $BLR_2$ , and the other is electrically connected to the terminal 14. One of the source and the drain of the transistor 34 is connected to the first bit line  $BLL_2$ , and the other is electrically connected to the terminal 17 via a plug 601. One of the source and the drain of the transistor 35 is electrically connected to the second bit line  $BLR_2$ , and the other is electrically connected to the terminal 18 via a plug 602.

(Write Operation)

Data are written to the magnetoresistive elements 22 and 24 of the memory cell  $1_{11}$  by causing a write current to flow between the source line  $SL_1$  and the first bit line  $BLL_1$ , and between the source line  $SL_1$  and the second bit line  $BLR_1$  via the conductive layer 10. The write currents for writing, for example, data "0" and data "1" to the magnetoresistive elements 22 and 24 are indicated by solid line arrows in FIG. 58. If data are to be written in an opposite manner, the directions of the write currents are opposite to the solid line arrows. As in the thirteenth embodiment, the write word line  $WWL_1$  is made active, and the write word line  $WWL_2$  is made inactive.

In this manner, different data are written to the magnetoresistive elements 22 and 24 of each memory cell.

(Read Operation)

Data are read from the magnetoresistive elements 22 and 24 of the memory cell  $1_{11}$  by causing read currents to flow from the source line  $SL_1$  to the magnetoresistive elements 22 and 24 via the conductive layer 10 as shown by broken line arrows in FIG. 58, and then causing the read currents to flow from the terminals 17 and 18 to the first bit line  $BLL_1$  and the second bit line  $BLR_1$  via the transistors 34 and 35. A

## 33

differential amplifier determines a resistance value using a difference in resistance between the magnetoresistive elements **22** and **24** to read the data state.

Similarly to the thirteenth embodiment, energy consumption may be reduced and write and read operation may be performed at a high speed in the magnetic memory in the eighteenth embodiment.

## Nineteenth Embodiment

A magnetic memory according to a nineteenth embodiment will be described with reference to FIGS. **59** and **60**. FIG. **59** is a plan view of the magnetic memory according to the nineteenth embodiment, and FIG. **60** is a cross-sectional view taken along line A-A of FIG. **59**.

The magnetic memory according to the nineteenth embodiment includes at least four memory cells  $1_{11}$  to  $1_{22}$ . Each memory cell  $1_{ij}$  ( $i, j=1, 2$ ) has the same configuration as the memory cells according to the eighteenth embodiment. The transistors **31**, **32**, **34**, and **35** included in each memory cell  $1_{ij}$  ( $i, j=1, 2$ ) are vertical transistors. The transistors **31** and **32** are disposed on the same level, and the transistors **34** and **35** are disposed on a higher level.

Unlike the magnetic memory according to the eighteenth embodiment, first and second write bit lines  $WBLL_1$  and  $WBLR_1$  and first and second read bit lines  $RBLL_1$  and  $RBLR_1$  are provided for the memory cells  $1_{i1}$  ( $i=1, 2$ ). First and second write bit lines  $WBLL_2$  and  $WBLR_2$  and first and second read bit lines  $RBLL_2$  and  $RBLR_2$  are provided for the memory cells  $1_{i2}$  ( $i=1, 2$ ). The write bit lines  $WBLL_1$ ,  $WBLR_1$ ,  $WBLL_2$ , and  $WBLR_2$  are disposed on a lower level.

In the memory cells  $1_{i1}$  ( $i=1, 2$ ), one of the source and the drain of the transistor **31** is connected to the first write bit line  $WBLL_1$ , the other is connected to the terminal **12**, and the gate is connected to the write word line  $WWL_1$ . One of the source and the drain of the transistor **32** is connected to the second write bit line  $WBLR_1$ , the other is connected to the terminal **14**, and the gate is connected to the write word line  $WWL_1$ . The terminal **12** and the terminal **14** are connected to the conductive layer **10**. The source line  $SL_1$  is connected to a region on the lower surface of the conductive layer **10** between the terminal **12** and the terminal **14**. The magnetoresistive elements **22** and **24** are disposed on the top surface of the conductive layer **10**, and the source line  $SL_1$  is disposed in the region on the lower surface of the conductive layer **10** corresponding to a region between the magnetoresistive element **22** and the magnetoresistive element **24**. The magnetoresistive element **22** is connected to the terminal **17** disposed on the upper level, and the magnetoresistive element **24** is connected to the terminal **18** disposed on the upper level. The transistor **34** is disposed above the terminal **17**. One of the source and the drain of the transistor **34** is connected to the terminal **17** via a plug **601**, the other is connected to the first read bit line  $RBLL_1$ , and the gate is connected to the read word line  $RWL_1$ . The first read bit line  $RBLL_1$  is disposed above the transistor **34**. The transistor **35** is disposed above the terminal **18**. One of the source and the drain of the transistor **35** is connected to the terminal **18** via a plug **602**, the other is connected to the second read bit line  $RBLR_1$ , and the gate is connected to the read word line  $RWL_1$ . The second read bit line  $RBLR_1$  is disposed above the transistor **35**.

Similarly, in the memory cells  $1_{i2}$  ( $i=1, 2$ ), one of the source and the drain of the transistor **31** is connected to the first write bit line  $WBLL_2$ , the other is connected to the terminal **12**, and the gate is connected to the write word line

## 34

$WWL_1$ . One of the source and the drain of the transistor **32** is connected to the second write bit line  $WBLR_2$ , the other is connected to the terminal **14**, and the gate is connected to the write word line  $WWL_1$ . The terminal **12** and the terminal **14** are connected to the conductive layer **10**. The source line  $SL_1$  is connected to a region on the lower surface of the conductive layer **10** between the terminal **12** and the terminal **14**. The magnetoresistive elements **22** and **24** are disposed on the top surface of the conductive layer **10**, and the source line  $SL_1$  is disposed in the region on the lower surface of the conductive layer **10** corresponding to a region between the magnetoresistive element **22** and the magnetoresistive element **24**. The magnetoresistive element **22** is connected to the terminal **17** disposed on an upper level, and the magnetoresistive element **24** is connected to the terminal **18** disposed on the upper level. The transistor **34** is disposed above the terminal **17**. One of the source and the drain of the transistor **34** is connected to the terminal **17** via a plug **601**, the other is connected to the first read bit line  $RBLL_1$ , and the gate is connected to the read word line  $RWL_1$ . The first read bit line  $RBLL_1$  is disposed above the transistor **34**. The transistor **35** is disposed above the terminal **18**. One of the source and the drain of the transistor **35** is connected to the terminal **18** via a plug **602**, the other is connected to the second read bit line  $RBLR_1$ , and the gate is connected to the read word line  $RWL_1$ . The second read bit line  $RBLR_1$  is disposed above the transistor **35**.

(Write Operation)

Data is written in the following manner to the memory cell  $1_{11}$  of the magnetic memory according to the nineteenth embodiment having the above configuration.

Data is written to the memory cell  $1_{11}$  by causing a write current to flow between the source line  $SL_1$  and the first write bit line  $WBLL_1$  and between the source line  $SL_1$  and the second write bit line  $WBLR_1$  via the conductive layer **10**. Solid line arrows in FIG. **60** indicate write currents in a case where data "0" is written to the magnetoresistive element **22** and data "1" is written to the magnetoresistive element **24**. If data are written to the respective magnetoresistive elements in an opposite manner, the directions of the write currents become opposite to the solid line arrows. As in the case of the thirteenth embodiment, the write word line  $WWL_1$  is caused to be active, and the write word line  $WWL_2$  is caused to be inactive.

(Read Operation)

Data is read from the memory cell  $1_{11}$  in the following manner.

As indicated by broken line arrows in FIG. **60**, read currents are caused to flow from the source line  $SL_1$  to the magnetoresistive elements **22** and **24** via the conductive layer **10**, and from the terminals **17** and **18** to the first read bit line  $RBLL_1$  and the second read bit line  $RBLR_1$  via the transistors **34** and **35**. A differential amplifier determines a resistance value using a difference in resistance between the magnetoresistive elements **22** and **24** to read the state of data.

The area occupied by the memory cells of the magnetic memory in the nineteenth embodiment is a half of the area in the eighteenth embodiment.

Similarly to the thirteenth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the nineteenth embodiment.

## Twentieth Embodiment

A magnetic memory according to a twentieth embodiment will be described with reference to FIGS. **61** and **62**. The

magnetic memory according to the twentieth embodiment includes at least one memory cell. FIG. 61 is a cross-sectional view of the memory cell, and FIG. 62 is a perspective view of the memory cell.

The memory cell 1 according to the twentieth embodiment has the same configuration as the memory cells 1<sub>1</sub> and 1<sub>2</sub> according to the thirteenth embodiment shown in FIG. 46. Thus, the memory cell 1 according to the twentieth embodiment includes a conductive layer 10, terminals (electrodes) 12 and 14 separately disposed on and connected to the conductive layer 10, terminals (electrodes) 16, 17, and 18, magnetoresistive elements 22 and 24 separately disposed in a region of the conductive layer 10 between the terminal 12 and the terminal 14, and transistors 31, 32, 34, and 35.

The magnetoresistive element 22 includes a storage layer 22a disposed on the conductive layer 10, a nonmagnetic layer 22b disposed on the storage layer 22a, and a reference layer 22c disposed on the nonmagnetic layer 22b. The magnetoresistive element 24 includes a storage layer 24a disposed on the conductive layer 10, a nonmagnetic layer 24b disposed on the storage layer 24a, and a reference layer 24c disposed on the nonmagnetic layer 24b.

The terminal 16 is electrically connected to a region of the conductive layer 10 between the magnetoresistive element 22 and the magnetoresistive element 24. The terminal 16 and the magnetoresistive elements 22 and 24 are electrically insulated from one another by sidewall insulating layers 40. A first bit line BLL is disposed on a region of the conductive layer 10 via an insulating layer 90a, the region being opposite to the terminal 16 relative to the magnetoresistive element 22. The first bit line BLL and the magnetoresistive element 22 are electrically insulated from each other by the sidewall insulating layer 40. A second bit line BLR is disposed on a region of the conductive layer 10 via an insulating layer 90b, the region being opposite to the terminal 16 relative to the magnetoresistive element 24. The second bit line BLR and the magnetoresistive element 24 are electrically insulated from each other by the sidewall insulating layer 40.

As shown in FIG. 62, the transistors 31 and 34 are disposed on a first semiconductor layer, and the transistors 32 and 35 are disposed on a second semiconductor layer that is isolated from the first semiconductor layer. One of the source and the drain (terminal) 31a of the transistor 31 is the same as one of the source and the drain (terminal) 34a of the transistor 34. One of the source and the drain (terminal) 32a of the transistor 32 is the same as one of the source and the drain (terminal) 35a of the transistor 35.

As shown in FIGS. 61 and 62, the other of the source and the drain (terminal) 31b of the transistor 31 is connected to the terminal 12, the terminal 31a is connected to the first bit line BLL via a plug 620, and the gate is connected to the write word line WWL. The other of the source and the drain (terminal) 32b of the transistor 32 is connected to the terminal 14, the terminal 32a is connected to the second bit line BLR via a plug 622, and the gate is connected to the write word line WWL.

The other of the source and the drain (terminal) 34b of the transistor 34 is connected to the terminal 17 via plugs 624, 626, and 628, the terminal 34a is connected to the first bit line BLL via the plug 620, and the gate is connected to the read word line RWL. The other of the source and the drain (terminal) 35b of the transistor 35 is connected to the terminal 18 via plugs 634, 636, and 638, the terminal 35a is connected to the second bit line BLR via the plug 622, and

the gate is connected to the read word line RWL. In this embodiment, the terminal 16 corresponds to the source line SL.

In the twentieth embodiment, the first bit line BLL, the source line SL, and the second bit line BLR connecting to the magnetoresistive elements 22 and 24 are disposed on the same level as the magnetoresistive elements 22 and 24, and are adjacent to the magnetoresistive elements 22 and 24. As a result, the occupied area of the magnetoresistive elements 22 and 24 can be reduced to  $(6F)^2$ , where F is a minimum feature size. Thus, the memory cells may be densely disposed.

Similarly to the thirteenth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the twentieth embodiment.

#### Twenty-First Embodiment

FIG. 63 illustrates a memory cell of a magnetic memory according to a twenty-first embodiment. The magnetic memory according to the twenty-first embodiment includes at least one memory cell 1, which has a configuration obtained by disposing the terminal 16 of the memory cell 1 according to the eighth embodiment shown in FIG. 18 to the lower surface of the conductive layer 10, and newly adding a dummy magnetoresistive element 26 and electrodes 27 and 28 to a region of the conductive layer 10 between the magnetoresistive element 22 and the magnetoresistive element 24. The dummy magnetoresistive element 26 has the same configuration as the magnetoresistive elements 22 and 24.

The dummy magnetoresistive element 26 is disposed in a region of the conductive layer 10 between the magnetoresistive element 22 and the magnetoresistive element 24. The electrode 27 is disposed in a region of the conductive layer 10 between the magnetoresistive element 22 and the dummy magnetoresistive element 26, and the electrode 28 is disposed in a region of the conductive layer 10 between the dummy magnetoresistive element 26 and the magnetoresistive element 24. A sidewall insulating layer 40b is disposed between a side portion of the magnetoresistive element 22 and a side portion of the electrode 27, a sidewall insulating layer 40e is disposed between a side portion of the electrode 27 and a side portion of the dummy magnetoresistive element 26, a sidewall insulating layer 40f is disposed between a side portion of the dummy magnetoresistive element 26 and a side portion of the electrode 28, and a sidewall insulating layer 40d is disposed between a side portion of the electrode 28 and a side portion of the magnetoresistive element 24.

An insulating layer 92a is disposed between the electrode 27 and the conductive layer 10, and an insulating layer 92b is disposed between the electrode 28 and the conductive layer 10 in this embodiment.

The dummy magnetoresistive element 26 is disposed between the magnetoresistive element 22 and the magnetoresistive element 24 so that the magnetoresistive elements 22, 26, and 24 are arranged with the same pitch in the twenty-first embodiment. As a result, the magnetic memory may be manufactured easily.

(First Modification)

FIG. 64 illustrates a memory cell of a magnetic memory according to a first modification of the twenty-first embodiment. The magnetic memory 1 according to the first modification includes at least one memory cell 1 having a configuration obtained by replacing the dummy magnetore-

sistive element 26 and the electrodes 27 and 28 with a dummy electrode 29 in the memory cell according to the twenty-first embodiment shown in FIG. 62. The dummy electrode 29 is formed of the same material as the electrodes 12 and 14, and is not electrically connected to any of the wiring lines.

The dummy electrode 29 in the first modification is disposed in a region of the conductive layer 10 between the magnetoresistive element 22 and the magnetoresistive element 24 so that the electrodes 12, 29, and 14 are arranged with the same pitch. As a result, the magnetic memory may be manufactured easily.

(Second Modification)

FIG. 65 illustrates a memory cell of a magnetic memory according to a second modification of the twenty-first embodiment. The magnetic memory according to the second modification includes at least one memory cell 1, which has a configuration obtained by increasing the width of a region of the dummy electrode 29 in contact with the conductive layer 10, so as to increase the contact area between the dummy electrode 29 and the conductive layer 10 in the memory cell according to the first modification shown in FIG. 64. This means that the width of the region of the dummy electrode 29 in the direction along which the conductive layer 10 extends is made longer than the width of a region of the electrode 16, which is in contact with the conductive layer 10.

The electric resistance of the dummy electrode 29 is generally lower than that of the conductive layer 10. Therefore, the write current flowing from the electrode 16 toward the conductive layer 10 tends to flow to the dummy electrode 29 rather than to the conductive layer 10. Therefore, most of the write current flows to the conductive layer 10 from the corner portions of the magnetoresistive elements 22 and 24 on the dummy electrode 29 side. Accordingly, if the position of the electrode 16 relative to the magnetoresistive elements 22 and 24 is moved, the influence of the movement can be effectively prevented. As a result, the magnetic memory may be manufactured easily.

(Third Modification)

FIG. 66 illustrates a memory cell of a magnetic memory according to a third modification of the twenty-first embodiment. The memory cell 1 according to the third modification is obtained by decreasing the thickness of the region of the conductive layer 10 that is in contact with the dummy electrode 29 to be thinner than the thickness of the regions of the conductive layer 10 immediately below the magnetoresistive elements 22 and 24 in the memory cell 1 according to the second modifications shown in FIG. 65.

Similarly to the second modification, the magnetizations of the magnetoresistive elements 22 and 24 may be switched easily in the third modification.

(Fourth Modification)

FIG. 67 illustrates a memory cell of a magnetic memory according to a fourth modification of the twenty-first embodiment. The memory cell 1 according to the fourth modification has a configuration obtained by removing the region of the conductive layer 10 that is in contact with the dummy electrode 29 in the memory cell 1 according to the second modification shown in FIG. 65 so that the dummy electrode 29 is in directly contact with the electrode 16.

Similarly to the second modification, the magnetizations of the magnetoresistive elements 22 and 24 may be switched easily in the fourth modification.

(Fifth Modification)

FIG. 68 illustrates a memory cell of the magnetic memory according to a fifth modification of the twenty-first embodi-

ment. The memory cell 1 according to the fifth modification has a configuration obtained by dividing the conductive layer 10 of the memory cell 1 according to the second modification shown in FIG. 65 into two conductive layers 10a and 10b, disposing the electrode 12 and the magnetoresistive element 22 on the conductive layer 10a, disposing the electrode 14 and the magnetoresistive element 24 on the conductive layer 10b, causing a part of the dummy electrode 29 to be in direct contact with the electrode 16, and causing the other part of the dummy electrode 29 to be in contact with the conductive layers 10a and 10b. With this configuration, aligning the electrodes 12, 14, and 16 does not require a high accuracy, and the magnetic memory may be manufactured easily.

Similarly to the second modification, the magnetizations of the magnetoresistive elements 22 and 24 may be switched easily in the fifth modification.

(Sixth Modification)

FIG. 69 illustrates a memory cell of a magnetic memory according to a sixth modification of the twenty-first embodiment. The memory cell 1 according to the sixth modification has a configuration obtained by dividing the conductive layer 10 of the memory cell 1 according to the second modification shown in FIG. 65 into three conductive layers 10a, 10b, and 10c, disposing the electrode 12 and the magnetoresistive element 22 on the conductive layer 10a, disposing the electrode 14 and the magnetoresistive element 24 on the conductive layer 10b, causing a part of the electrode 16 to be in direct contact with a part of the dummy electrode 29, and causing the other part of the electrode 16 to be in direct contact with the conductive layer 10c. With this configuration, aligning the electrodes 12, 14, and 16 does not require a high accuracy, and the magnetic memory may be manufactured easily.

Similarly to the second modification, the magnetizations of the magnetoresistive elements 22 and 24 may be switched easily in the sixth modification.

(Seventh Modification)

FIG. 70 illustrates a memory cell of a magnetic memory according to a seventh modification of the twenty-first embodiment. The memory cell 1 according to the seventh modification has a configuration obtained by disposing a terminal (electrode) 17 that is electrically connected to the reference layer of the magnetoresistive element 22 and a terminal (electrode) 18 that is electrically connected to the reference layer of the magnetoresistive element 24 in the memory cell 1 according to the second modification shown in FIG. 65. The terminals 17 and 18 are formed in an insulating film 280 disposed to cover the electrodes 12 and 14 and the magnetoresistive elements 22 and 24.

Similarly to the second modification, the magnetizations of the magnetoresistive elements 22 and 24 may be switched easily in the sixth modification.

Similarly to the eighth embodiment, energy consumption may be reduced and write and read operations may be performed at a high speed in the magnetic memory according to the twenty-first embodiment and the first to seventh modifications of the twenty-first embodiment.

While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to

cover such forms or modifications as would fall within the scope and spirit of the inventions.

The invention claimed is:

1. A magnetic memory comprising:  
a first terminal, a second terminal, and a third terminal;  
a first conductive layer including first to fifth regions, the second region being between the first region and the fifth region, the third region being between the second region and the fifth region, the fourth region being between the third region and the fifth region, the first region being electrically connected to the first terminal, the fifth region being electrically connected to the second terminal, and the third region being electrically connected to the third terminal;  
a first magnetoresistive element disposed corresponding to the second region, the first magnetoresistive element including a first magnetic layer, a second magnetic layer disposed between the second region and the first magnetic layer, a first nonmagnetic layer disposed between the first magnetic layer and the second magnetic layer, and a fourth terminal electrically connected to the first magnetic layer;  
a second magnetoresistive element disposed corresponding to the fourth region, the second magnetoresistive element including a third magnetic layer, a fourth magnetic layer disposed between the fourth region and the third magnetic layer, a second nonmagnetic layer disposed between the third magnetic layer and the fourth magnetic layer, and a fifth terminal electrically connected to the third magnetic layer; and  
a circuit configured to flow a write current between the first terminal and the third terminal and between the second terminal and the third terminal in a write operation.
2. The magnetic memory according to claim 1, wherein the circuit applies a same potential to the fourth terminal and the fifth terminal in the write operation.
3. The magnetic memory according to claim 1, wherein the circuit applies a voltage between the fourth terminal and the fifth terminal, and performs a read operation based on a potential of the third terminal.
4. The magnetic memory according to claim 1, wherein the third terminal is disposed on the first conductive layer on an opposite side to a side on which the first magnetoresistive element and the second magnetoresistive element are disposed.
5. The magnetic memory according to claim 4, further comprising a third magnetoresistive element disposed corresponding to the third region on an opposite side to a side on which the third magnetoresistive element including a fifth magnetic layer, a sixth magnetic layer disposed between the third region and the fifth magnetic layer, and a third nonmagnetic layer disposed between the fifth magnetic layer and the sixth magnetic layer.
6. The magnetic memory according to claim 4, further comprising a second conductive layer having a higher conductivity than the first conductive layer, the second conductive layer being disposed on the third region on an opposite side to the third terminal.
7. The magnetic memory according to claim 1, wherein the third terminal is disposed on the third region of the first conductive layer on the same side as a side on which the first magnetoresistive element and the second magnetoresistive element are disposed.

8. The magnetic memory according to claim 7, wherein at least one of the first terminal, the second terminal, and the third terminal includes a metal magnetic layer.

9. The magnetic memory according to claim 1, wherein the circuit flows a read current between the third terminal and the fourth terminal and between the third terminal and the fifth terminal, and performs a read operation on the basis of a potential difference or a current difference between the fourth terminal and the fifth terminal.

10. The magnetic memory according to claim 1, wherein the first terminal and the second terminal are electrically connected with each other.

11. The magnetic memory according to claim 1, further comprising a magnetic field application device, wherein the second magnetic layer and the fourth magnetic layer have a perpendicular magnetic anisotropy, and the magnetic field application device applies a first magnetic field to the second magnetic layer and a second magnetic field to the fourth magnetic layer, the first magnetic field including a first component and the second magnetic field including a second component, the first component and the second component being perpendicular to a layer stacking direction of the first magnetoresistive element and the second magnetoresistive element.

12. The magnetic memory according to claim 1, further comprising a magnetic field application device, wherein the second magnetic layer and the fourth magnetic layer have an in-plane magnetic anisotropy, and the magnetic field application device applies a first magnetic field to the second magnetic layer and a second magnetic field to the fourth magnetic layer, the first magnetic field including a first component and the second magnetic field including a second component, the first component and the second component being parallel to a layer stacking direction of the first magnetoresistive element and the second magnetoresistive element.

13. The magnetic memory according to claim 1, wherein the second magnetic layer and the fourth magnetic layer have an in-plane magnetic anisotropy, and an angle made by an easy magnetization axis of each of the second magnetic layer and the fourth magnetic layer and a direction in which the write current flows is more than 0 degree and less than 45 degrees.

14. A magnetic memory comprising:

- a first terminal, a second terminal, and a third terminal;
- a conductive layer including first to fifth regions, the second region being between the first region and the fifth region, the third region being between the second region and the fifth region, the fourth region being between the third region and the fifth region, the first region being electrically connected to the first terminal, the fifth region being electrically connected to the second terminal, and the third region being electrically connected to the third terminal;
- a first magnetoresistive element disposed corresponding to the second region, the first magnetoresistive element including a first magnetic layer, a second magnetic layer disposed between the second region and the first magnetic layer, a first nonmagnetic layer disposed between the first magnetic layer and the second magnetic layer, and a fourth terminal electrically connected to the first magnetic layer;
- a second magnetoresistive element disposed corresponding to the fourth region, the second magnetoresistive element including a third magnetic layer, a fourth magnetic layer disposed between the fourth region and the third magnetic layer, a second nonmagnetic layer

## 41

- disposed between the third magnetic layer and the fourth magnetic layer, and a fifth terminal electrically connected to the third magnetic layer;
- a circuit configured to flow a write current between the first terminal and the second terminal in a write operation; and
- a magnetic field application device configured to apply a first magnetic field to the second magnetic layer and a second magnetic field to the fourth magnetic layer, the first magnetic field including a first component and the second magnetic field including a second component, the first component and the second component being perpendicular to a layer stacking direction of the first magnetoresistive element and the second magnetoresistive element, the first component and the second component being in opposite directions each other.
- 15.** The magnetic memory according to claim **14**, wherein the circuit applies a voltage to the fourth terminal and the fifth terminal in the write operation.
- 16.** The magnetic memory according to claim **14**, wherein the circuit applies a voltage between the fourth terminal and the fifth terminal, and performs a read operation based on a potential of the third terminal.
- 17.** A magnetic memory comprising:
- a first terminal and a second terminal;
  - a first conductive layer including a first region, a second region, and a third region, the second region being between the first region and the third region, and the first region being electrically connected to the first terminal;
  - a second conductive layer including a fourth region, a fifth region, a sixth region, the fifth region being between the fourth region and the sixth region, and the sixth region being electrically connected to the second terminal;
  - a third terminal electrically connected to the third region and the fourth region;
  - a first magnetoresistive element disposed corresponding to the second region and including a first magnetic layer, a second magnetic layer disposed between the second region and the first magnetic layer, a first nonmagnetic layer disposed between the first magnetic layer and the second magnetic layer, and a fourth terminal electrically connected to the first magnetic layer;
  - a second magnetoresistive element disposed corresponding to the fifth region and including a third magnetic layer, a fourth magnetic layer disposed between the fifth region and the third magnetic layer, a second nonmagnetic layer disposed between the third magnetic layer and the fourth magnetic layer, and a fifth terminal electrically connected to the third magnetic layer; and
  - a circuit configured to flow a write current between the first terminal and the second terminal via the first conductive layer and the second conductive layer in a write operation.
- 18.** The magnetic memory according to claim **17**, wherein a sign of a spin Hall angle of the first conductive layer is different from a sign of a spin Hall angle of the second conductive layer.
- 19.** The magnetic memory according to claim **17**, wherein the second conductive layer is disposed above the first conductive layer, the first magnetoresistive element is disposed between the second conductive layer and the first conductive layer, and the second magnetoresistive element is disposed above the first magnetoresistive element.

## 42

- 20.** A magnetic memory comprising:
- a first terminal, a second terminal, and a third terminal;
  - a conductive layer including first to fifth regions, the second region being between the first region and the fifth region, the third region being between the second region and the fifth region, the fourth region being between the third region and the fifth region, the first region being electrically connected to the first terminal, the fifth region being electrically connected to the second terminal, and the third region being electrically connected to the third terminal;
  - a first magnetoresistive element disposed corresponding to the second region, the first magnetoresistive element including a first magnetic layer, a second magnetic layer disposed between the second region and the first magnetic layer, a first nonmagnetic layer disposed between the first magnetic layer and the second magnetic layer, and a fourth terminal electrically connected to the first magnetic layer;
  - a second magnetoresistive element disposed corresponding to the fourth region, the second magnetoresistive element including a third magnetic layer, a fourth magnetic layer disposed between the fourth region and the third magnetic layer, a second nonmagnetic layer disposed between the third magnetic layer and the fourth magnetic layer, and a fifth terminal electrically connected to the third magnetic layer; and
  - a circuit configured to flow a write current between the first terminal and the third terminal and between the second terminal and the third terminal in a first write operation for writing to the first magnetoresistive element and the second magnetoresistive element, and to flow a write current between the first terminal and the second terminal in a second write operation for writing to the first magnetoresistive element and the second magnetoresistive element.
- 21.** The magnetic memory according to **20**, wherein in the first write operation, different data are written to the first magnetoresistive element and the second magnetoresistive element, and in the second write operation, identical data are written to the first magnetoresistive element and the second magnetoresistive element.
- 22.** A magnetic memory comprising:
- a first terminal and a second terminal;
  - a first conductive layer including first to third regions disposed in a first direction, the second region being between the first region and the third region, and the first region being electrically connected to the first terminal;
  - a second conductive layer including a fourth to sixth regions disposed in the first direction, the fifth region being between the fourth region and the sixth region, and the sixth region being electrically connected to the second terminal;
  - a third conductive layer electrically connected to the third region and the fourth region;
  - a first magnetoresistive element disposed corresponding to the second region and including a first magnetic layer, a second magnetic layer disposed between the second region and the first magnetic layer, a first nonmagnetic layer disposed between the first magnetic layer and the second magnetic layer, and a third terminal electrically connected to the first magnetic layer;
  - a second magnetoresistive element disposed corresponding to the fifth region and including a third magnetic layer, a fourth magnetic layer disposed between the fifth region and the third magnetic layer, a second

nonmagnetic layer disposed between the third magnetic layer and the fourth magnetic layer, and a fourth terminal electrically connected to the third magnetic layer; and  
a first circuit configured to flow a write current between 5  
the first terminal and the second terminal via the first  
conductive layer, the third conductive layer, and the  
second conductive layer in a write operation,  
wherein a direction from the first region to the third region  
is different from a direction from the fourth region to 10  
the sixth region each other.

\* \* \* \* \*